Methods to Improve School Design in Sierra Leone

by

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ABSTRACT

Most schools in Sierra Leone are constructed using a standard design with little variation from building to building. They are relatively high-cost and have poor ventilation, lighting and thermal comfort. In January 2010, thirteen primary schools in Sierra Leone were analyzed in order to identify design changes that will improve performance and reduce costs. One struggle that this analysis revealed is that construction methods have not changed for decades, as local builders resist changes in the current design. This thesis aims to explain small-scale alterations for primary school buildings in Sierra Leone and list the impact on daylighting and thermal comfort performance for each alteration. For each design alteration, the daylight performance, air flow, and thermal comfort of the new design are compared to the standard design. The overall goal of this thesis is to create guidelines that can be used to reduce the risk of design changes and improve the performance of schools without raising costs.

Thesis Supervisor: Leslie K. Norford
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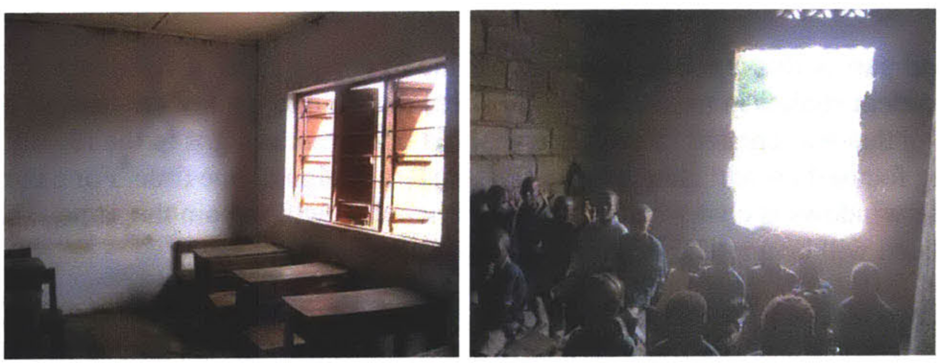
Chapter 1
Introduction

1.1 Motivation

The colonial-style school design and construction methods in Sierra Leone have not been changed for decades and rely heavily on imported materials. Local builders and non-profits are hesitant to invest in a building that has no precedent in the region, yet the performance of the current design is lacking. Anecdotal evidence has shown that some schools conduct their classes outdoors during a portion of the day because the rooms are too dark to read and write in (figures 1 & 2). When it rains, the shutters must be closed, allowing very little light into the classroom. Additionally, many of the construction materials are imported, rather than taking advantage of local materials and labor. If areas for improvement in the current design were identified, the performance could be enhanced and the costs could be lowered, thus making it possible to build more schools. A manual that simply explains building changes would give developers the information needed to improve current designs without taking large risks.



Figures 1&2: Examples of schools with low lighting quality

1.2 Objectives of this study

Because the culture, climate, and building practices vary significantly from region to region, this thesis focuses specifically on the Port Loko district of Sierra Leone. Therefore, I will begin by introducing the recent history, geography, people, and education of Sierra Leone. Next, the documentation of schools conducted in Sierra Leone and how it serves as the basis for changes in the current building design will be explained.

In addition to identifying characteristics of the building performance that negatively affect the learning environment, the physical properties documented are used to create a "base" design. This base design is the starting point of the daylighting, ventilation, and cost analysis. Building characteristics for alterations were chosen after evaluating performance shortfalls of the current design. Each alteration is independent of others and compared to the base design for single changes. Therefore—the evaluation does not create a complete building design, but only evaluating single changes at one time. In addition to this report, the deliverables of this thesis include a book of guidelines that will use visual descriptions and simply explain the performance of design changes relative to the base design.

One use for this manual will be to allow non-profits who fund the construction of current schools to begin improvements in their design without being dissuaded by large, risky changes. Each change can be implemented one-at-a-time without changing other building elements, and the change can be proven successful in the field before further alterations are made to subsequent buildings. When applicable, a description of the change, the daylight performance and the thermal comfort is illustrated visually as well as with text. These guidelines also act as a summary of the thesis results.

1.3 Structure of this thesis

Chapter 1 of this report gives introduces the research project and gives a background of Sierra Leone. Chapter 2 documents thirteen current designs in Sierra Leone that were studied in depth during January 2010. The buildings analyzed were entirely passive, and therefore include no mechanical cooling systems or electric lighting. As a result, the interior light level is dependent upon the exterior light level and the properties of the building fenestration. Cooling of the interior is dependent on natural ventilation. This study found that most schools were constructed based on a standard design.

The second part of this report provides an outline of design alternatives that were created based on precedent studies in tropical regions. These design alternatives are used to compare to the base design that was created through the analysis of current designs in the region. Only one variable being focused on will change from the standard design at one time. For example, if the position of the windows is changed, the area of the window will remain the same. Therefore, the values calculated will be applicable without any other changes.

The next two sections provide an evaluation of the lighting quality, natural ventilation, and thermal comfort in one classroom. Each analysis uses the "base" design as a comparison for design alterations. The lighting simulations are carried out with LightSolve, the airflow through the window openings is analyzed with CONTAM Multizone Analysis Software, and the thermal comfort analysis is carried out with CONTAM as well as a combination of EnergyPlus and DesignBuilder.

The goals of the building changes are to increase adequate lighting levels, reduce interior heat gain, and increase the natural ventilation. A summary of each design is given at the end of this report, and the conclusions are written out in guideline format, comparing each alteration to the base design.

Where possible, cost implications of the designs are also noted in the final summary. The change in materials and costs will be estimated based on data obtained from previous construction projects in Sierra Leone, and the lighting performance and thermal comfort will be modeled with computer simulations. However, certain aspects of cost—such as a 15% government tax on all non-food items that was implemented in 2010 and rapid inflation that has been estimated at approximately 12% per year—make it necessary to compare cost estimates relative to the base design, rather than looking at them as a final sum (Nofzinger, 2010). Last, shortfalls in this report and areas for further research are discussed.

1.4 Sierra Leone

1.4.1 History

The capital of Sierra Leone, Freetown, was named after it was established as a refuge for smuggled slaves who were freed from slave ships in the Atlantic after the slave trade became illegal in 1808. Many of these settlers became known as Creoles, and were characterized by their English and Christianity that was brought into Freetown by missionaries.

Sierra Leone became independent from the British in 1961. Sierra Leone's diamonds, termed "blood diamonds" during the civil war, crippled the country with corruption and economic decay from the beginning of their independence. Civil wars between the different factions had plagued the country for decades, most recently with an 11 year civil war from 1991-2002, during which time approximately one-third of the population was displaced and an unknown number died (Bamber, 2010).

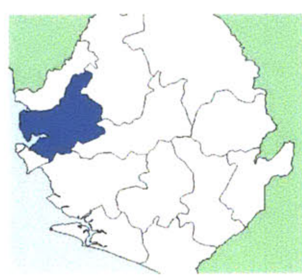
1.3.2 Location and Climate

Located on the Atlantic coast of Africa, Sierra Leone is bordered by Guinea to the northeast and Liberia to the southeast (figures 3 & 4). At 71,740 km^2, the country is slightly smaller than South Carolina. In the Port Loko district, where this report focuses on, the capitol and largest city is Lunsar. Because of its latitude at 8°N, the sun remains relatively high in the sky throughout the year and the climate is hot, with mean monthly temperatures ranging from 23-28°C. Sky illuminance averages around 55,000 lux on a clear day.[1] While the rainy season lasts from May to October, the rest of the year is relatively dry, making distinct agricultural seasons (DOE, 2010).

Table 1: Monthly averages for wind speed and temperature

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Wind speed (m/s)	4.46	4.27	4.47	4.48	4.94	4.48	4.47	3.99	3.93	3.34	3.51	3.63	**4.16**

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Temp. (°C)	26.7	27.6	27.7	27.1	25.4	24.4	23.6	23.5	24.0	24.4	24.3	24.9	**25.3**



Figures 3&4: Sierra Leone in relation to the Africa continent and the Port Loko district of Sierra Leone

[1] Calculated average of eighteen measurements taken in Lunsar, Sierra Leone.

1.3.3 People and Education

The official language of Sierra Leone is English, but it is only spoken by a small minority, leaving Mende, Temne, and Krio as the common languages. The dominant religion is Muslim, yet approximately 35% of the population is Christian, and marriage across tribal and religious boundaries is common. In the Port Loko district, the largest ethnic group and most common language is Temne.

According to the CIA World Fact Book, 35.1% of the population over fifteen can read and write. While the government is trying to increase school enrollment, the current shortage of teachers, buildings, and resources has made this difficult. The Bureau of International Labor Affairs has estimated that 1,270 primary schools were destroyed in Sierra Leone between 1991 and 2002 and that only 33% of children were able to attend school in 2001. Although this number improved dramatically since the civil war ended, in 2007, 25-30% of children still did not attend primary school, and fewer complete their primary education. According to the Ministries, Departments and Agencies (MDA) in Port Loko, there are 463 schools in the Port Loko district, with a teacher-student ratio at 1:91.

Chapter 2

Analysis of thirteen primary schools in the Port Loko district of Sierra Leone

In January 2010, 18 primary school structures in the Port Loko district of Sierra Leone were evaluated for thermal comfort, daylighting, and material use. Eighteen total schools were analyzed, however, only thirteen of these were deemed "standard" designs. What qualifies a building as "standard" is that it was originally built for the purpose of holding classes and that it is a permanent structure, meant to last longer than five years. The first qualification eliminates three buildings that were analyzed—the Kulafai Muslim Primary School, the Suzanne Mass Memorial Primary School, and the Josephine Bakhita Daycare for the Poor—all three of which were originally built for other purposes but converted into schools as the space was needed. The second qualification eliminated two temporary structures: the primary schools of Robomp and Robanka. Therefore, the remaining thirteen schools are considered to be standard designs.

Figure 5-7: Kulafai Muslim Primary School, the Suzanne Mass Memorial Primary School, and the Josephine Bakhita Daycare for the Poor

Figures 8 & 9: The primary schools of Robomp and Robanka.

Based on these precedent studies of local schools, a prototype primary school is created using average dimensions and standard characteristics. This prototype is used as a base from which design alterations are made to, and then compared to the original design for performance changes and to tabulate material and cost differences.

1.1 Classroom characteristics and layout

Characteristics looked at first were the number of classrooms, the dimension of each room, and the layout of the building (Appendix 1.1). Nine of the schools have six classrooms, three had four classrooms, and one had nine. The majority of the schools had six classrooms. Many of these also had additional storage and office spaces, but for this study, only the classrooms are evaluated. The average floor area of all 13 school classrooms was 6.2m x 8.0m, each orientated with the long wall facing outwards and the short wall being the joining wall to the adjacent classroom. The most common building layout was linear, although one was U-shaped, and three were L-shaped. See Appendix 1.3 for visual descriptions of layout types.

1.2 Material and structure

The materials of the walls, roofing, foundation, and windows for each building were documented. The documentation found that most official schools in Sierra Leone are constructed in a relatively similar fashion with a concrete foundation, concrete block walls, wooden trusses, and a corrugated zinc roof.

1.3 Daylighting

Measured on site was the size of the windows, the number of windows, and the percentage of open area in the windows. None of the windows have panes. The open area in the fenestration does not directly correlate with the quantity of light that the classrooms receive because of these different window types, especially the decorative screen windows (see figures 10-12). While these types of windows are not as common as open windows, they eliminate the need for additional security, which is sometimes implemented with rebar in the windows. The proportion of open area, and the shape of the opening, in each of these windows varies, therefore the total effects of this type of window cannot be measured by just the window area, as the wall thickness separating the window gaps diffuses the light in this window type, greatly reducing the amount of glare and direct sunlight.

Figures 10-12: Decorative screen windows that create diffuse lighting

The light levels of the classroom were measured quantitatively with a lux meter in nine points evenly dispersed throughout the classroom. Qualitative measurements were also taken, and each teacher was asked questions about the lighting performance. Overall, many of the current school designs have poor light qualities from excess glare and inadequate lighting levels. Because all the open windows (not including the screen windows, as exemplified in figures 10-12) had vertical (casement) shutters rather than horizontal (awning) shutters, the lighting control is most often limited to the thickness of the wall. At 8° latitude, the sun is mostly overhead during the day; therefore vertical shutters do little to reduce the direct sunlight. While assessing the schools, many teachers and principals noted that school is either canceled during heavy rains, or that some windows must be shut during lighter rains. In cases where the windows are shut during rains, very little light is able to penetrate into the classroom.

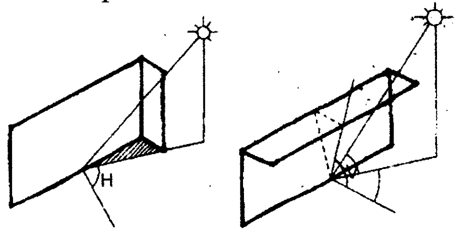


Figure 13: Examples of vertical shading devices vs. horizontal shading devices

1.4 Creating a base design

Based on the case studies of local schools, a prototype was created by averaging classroom and window dimensions and taking most commonly used features and materials. This prototype will be used as a base from which design alterations will be made to, and then compared to the original design for material, cost, and performance changes. The plan and model below (figures 14 and 15), consists of six classrooms in a linear array with a dimension of 6.2m x 8m, window dimensions of 1.6 x 1.1m, two vertical shutters on each window, and concrete columns.

Below are some problems with the base design that the design alterations aim to address:

- Very little overhead protection from direct heat gains on the rear side of the building
- Shutters on the rear side of the building must be closed during rains
- When the front shutters are opened, they block the front pathway
- Overcrowding within schools causes classrooms to head up substantially
- High glare within the classroom is distracting
- Light levels are not always adequate for reading and writing

However, some benefits to keeping the base design include:

- Builders are familiar with construction methods
- Current design is a safe choice for funding agencies and has precedent
- Local familiarity
- Tradition appearance

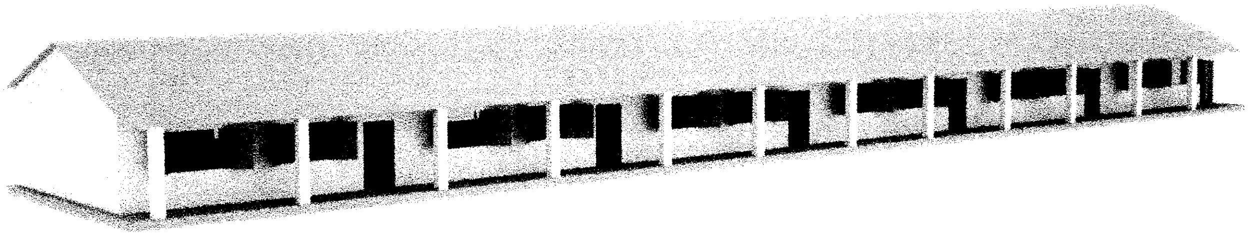


Figure 14: Model of base design

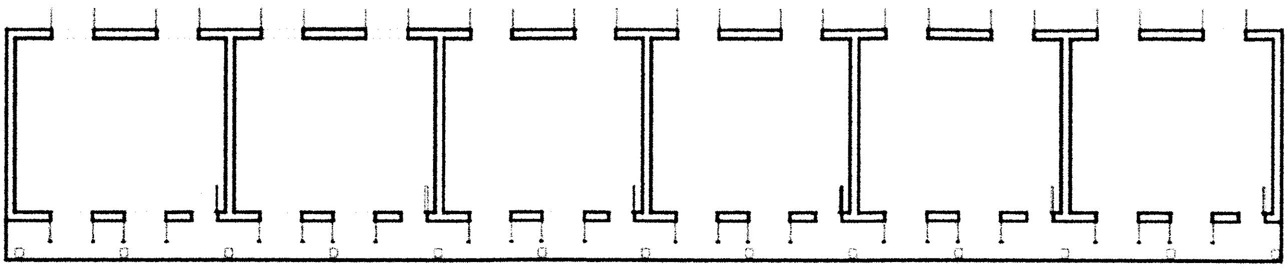


Figure 15: Floor plan of base design

Table 1 shows a list of characteristics averaged to create the standard design based on the buildings sampled. The majority of schools had a linear orientation and had six classrooms. Many of these also had additional storage and office spaces, but for this simplification, only the classrooms will be taken into account in this study. The average floor area of all 13 school classrooms was 6.2m x 8.0m, each orientated with the long wall facing outwards and the short wall being the joining wall to the adjacent classroom.

No	Name	Window Size (m)	# of Windows	Dimensions per room(m)	Wall	Truss	Roof	Column
1.	RC Kamasondo	1.2 x 0.9	3	5.5 x 6.1	Mud brick	wood	Zinc, new	none
2.	Romance Kamasondo	2.0 x 1.2	5	6.0 x 8.2	concrete	wood	Zinc, rusted	Square concrete
3.	West of Kamasondo	2.0 x 1.2	3	5.8 x 8.6	concrete	wood	Zinc, rusted	Square concrete
4.	Rosint School	1.4 x 1.4	3	5.8 x 8.3	concrete	wood	Zinc, rusted	none
5.	South of Rokholifa	2.0 x 1.2	3	7.1 x 9.1	concrete	wood	Zinc, rusted	Round concrete
6.	Ahmadiyya Muslim	1.4 x 1.1	4	6.2 x 8.8	concrete	wood	Zinc, rusted	Square concrete
7.	Holy Cross Catholic	1.1 x 1.1	5	6.7 x 8.0	concrete	steel	Zinc, rusted	steel
8.	Marampa Islamic School	1.1 x 1.0	4	5.5 x 6.5	concrete	steel	Zinc, rusted	steel
9.	District Council School	1.2 x 0.9	3	6.0 x 7.9	concrete	wood	Zinc, rusted	Square concrete
10.	Adele Pavariani, Lunsar	1.4 x 1.1	5	6.1 x 7.9	concrete	steel	Zinc, rusted	none
11.	Sierra Leone	1.8 x 1.1	5	6.2 x 8.7	concrete	wood	Zinc, rusted	steel
12.	Moslim Brotherhood	2.4 x 1.2	5	6.8 x 9.4	concrete	wood	Zinc, rusted	steel
13.	Catholic Mission	1.4 x 1.1	5	6.5 x 7.1	concrete	steel	Zinc, rusted	none
	Total Average	**1.6 x 1.1**	**4.1**	**6.2 x 8.0**	**concrete**	**wood**	**Zinc**	**concrete**

Table 2: Measurements and notes taken to create the standard design

Chapter 3

Alternative design formulation

3.1 Shading

3.1.1 Pivoting Shutters

For the pivoting shutter design, the classroom dimensions, window size, and roof size do not differ from the base design. Shutters that pivot rather than open horizontally can be adjusted to any angle and are stabilized with props that attach to the window sill. The shutter design could be made with a range of materials types, including wooden shutters at the same size as the base design. However, it is suggested that a lighter weight, such as metal or fiberglass material is used to make operation easier.

The most beneficial aspect to pivoting windows is being able to adjust the pivoting awning to different angles. For example, in rainy weather, the shutters may be angled down to prevent water from entering the classroom. If fully opened, the shutters may act as a light shelf, allowing sunlight to penetrate deeper into the classroom.

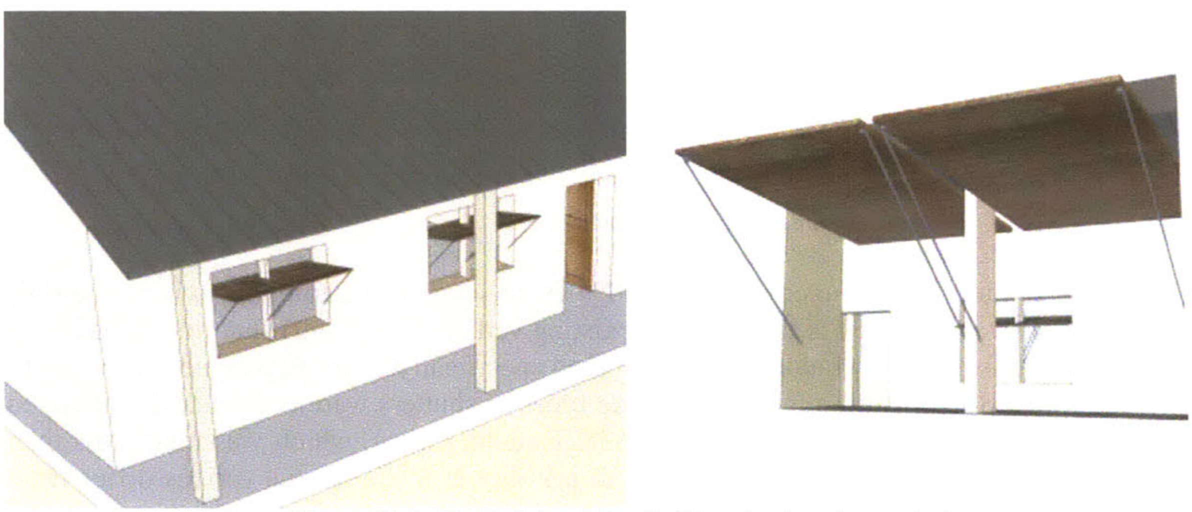


Figure 16 & 17: Model and detail of the pivoting shutter design

Benefits:

- Shutters provide overhead protection against direct sunlight
- User may adjust the shutters to a variety of angles
- Shutters can protect against rains while still allowing in daylight

Problems:

- The shutters do not protect against rain coming in at strong angles
- If shutters are too heavy, they could be difficult for young children to open
- Construction and design is not common, and therefore local builders would need training in the fabrication of the shutters, increasing labor costs.
- Pivoting shutters cannot be built in windows with rebar

A precedent to the pivoting shutter design is seen in the works of Laurie Baker, an English architect that lived and worked in India for most of his life. Below is a quote from Baker about simplifying windows (Bautam, 1991). Figure shows Baker's sketches.

> *The simplest window consists of a vertical plank set into two holes (or pivot hinges), one at the top and one at the bottom. The traditional design consists of two short wood pieces with a circular hole in each, and the vertical shutter has two small round protrusions (as shown on the left) to fit into the holes. Only a nine-inch wide hole is necessary for the 'window.' This is strong, simple, inexpensive, requires very little labour, no ironmongery, lets in light and air and provides security.*

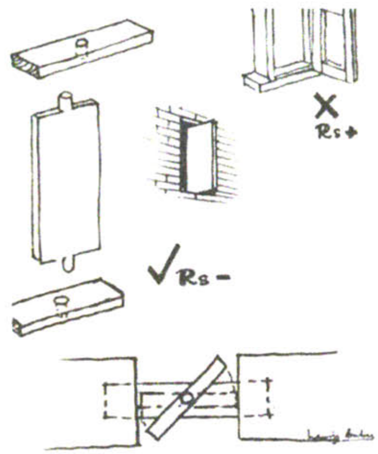


Figure 18: Drawings by Laurie Baker

Pivoting shutters were also created for MIT's D-lab schools in Cambodia, where a retrofit for current schools was designed to improve the existing vertical (casement) shutters that are also common in Cambodia. These windows were designed specifically to be adjustable according to weather conditions. Both awning-type and pivoting types of shutters were constructed and added to the classrooms. The cost of each shutter was $38, including labor, which was much less than the wooden shutters, which are approximately $55 per shutter in Cambodia (prices differ from estimated prices used for analysis in Sierra Leone).

Figure 19 & 20: Pivoting shutters by MIT D-lab

3.1.2 Awning Shutters

The second type of exterior shading device analyzed is awning shutters. These attach above the window and extend downward. While many awnings attached to buildings are permanently fixed, this design can close and lock, securing the inside of the building as well as protecting from direct sunlight. The benefit of awning shutters over pivoting shutters is that they can be installed onto windows along with rebar for added security, whereas rebar would stop the pivoting shutters from opening.

In addition to installing pivoting shutters, as seen in the previous section, MIT D-lab Schools constructed awning shutters at the same time (figure 21). These were also made of a metal frame with a sheet metal covering riveted to the frame. A window prop was attached with metal washers and bolts to the window frame, and bolts were welded at increments along the window frame to allow the prop to fix the shutter angle.

Another precedent, shown in figure 22, is the South Arica Ithuba Project, built in Johannesburg, South Africa. This project uses a series of awning windows stacked vertically and also allow for user adjustability.

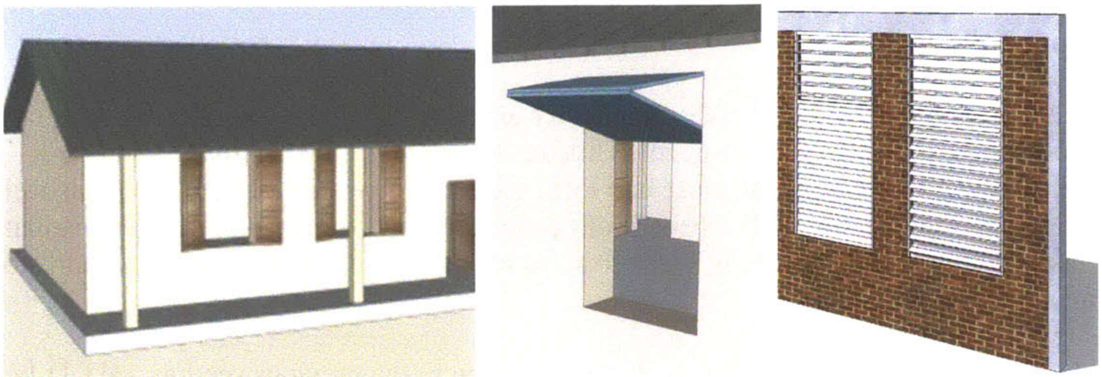
Figure 21: Awning shutters by MIT D-lab

Figure 22: Vertically stacked awning shutters by the South Africa Ithuba Project

3.2 Windows

3.2.1 Elongated Windows

With the same opening area as the base design, windows with a different shape—taller and narrower—will be evaluated against the base design (figures 23-25). Therefore, it is not the area of the windows that are being compared in the elongated windows design, but the orientation and shape of the windows. The number of windows is also the same as the base design. In terms of material, this alteration reduces the need for a reinforced concrete lintel above each window, which is a significant portion of total construction costs.



Figures 23-25: Renderings of long windows with standard, casement shutters vertical folding shutters, and blinds

A major benefit of this design is that higher windows allow light to penetrate deeper into the classroom. As a rule of thumb, light will penetrate a depth approximately 2-2.5 times the height of the window (figure 26, Gelfand & Freed, 2010). Wind flow is also changed with the height of the windows. Because the windows are open, wind-driven flows and buoyancy flows occur. With taller windows, buoyancy-driven flows are greater.

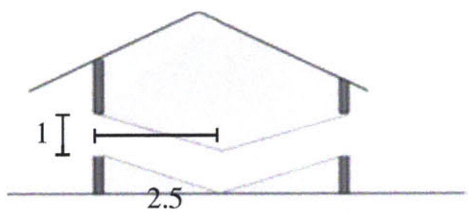


Figure 26: Rule of thumb ratio for window height to depth within the classroom that the light will reach

A challenge with this new window shape is the shutter design since they would need to be customized. Using wooden shutters would be a simple solution, as local carpenters customize current school shutters already. An alternative would be to have folding shutters or slatted louvers (figures 24 & 25) that would also provide shading as well. However, with the same costs for shutters, the elongated windows do reduce in concrete and steel material needed for the reinforced-concrete lintel above each window (figure 27).

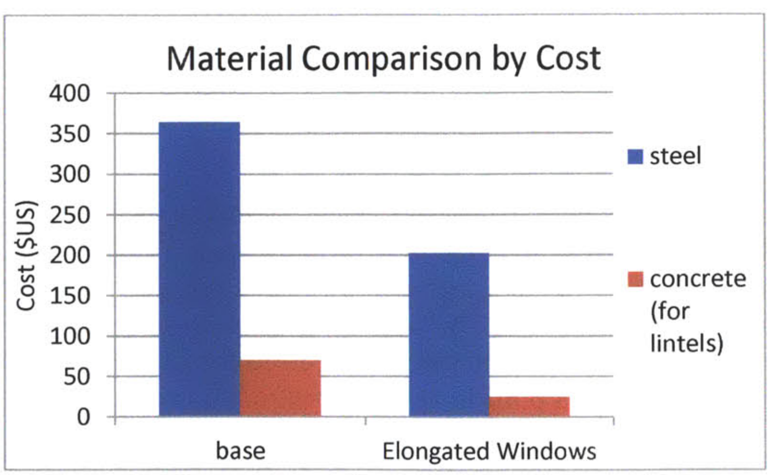


Figure 27: Cost comparison between the base design and the elongated windows design

One exemplary use of an elongated window design is in Burkina Faso, where the architect Diebedo Francis Kere designed a primary school. This designed used folding shutters that could also provide shading.

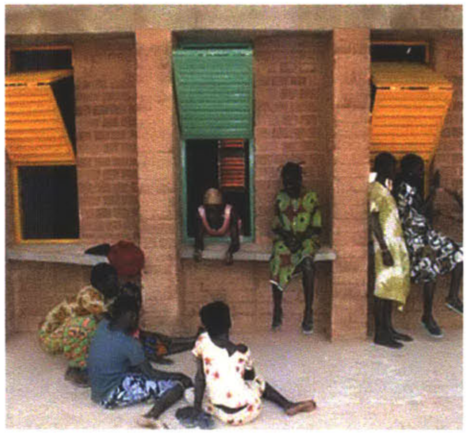


Figure 28: Primary School and extension at Gando, Burkina Faso by Diebedo Francis Kere

3.2.2 Jali Walls

"Screen" or "jali" windows (figure 29) are an alternative type of window that is common is Sierra Leone. While the traditional type of jali wall consists of bricks placed with gaps in between them, the screen walls in Sierra Leone are made with decorative concrete blocks. This type of window diffuses reduces glare and creates interesting light patterns inside the classroom. Like the elongated windows, these windows also do not need supporting lintels above them, since the bricks give additional support. A material comparison with cost estimates is shown in figure 30.

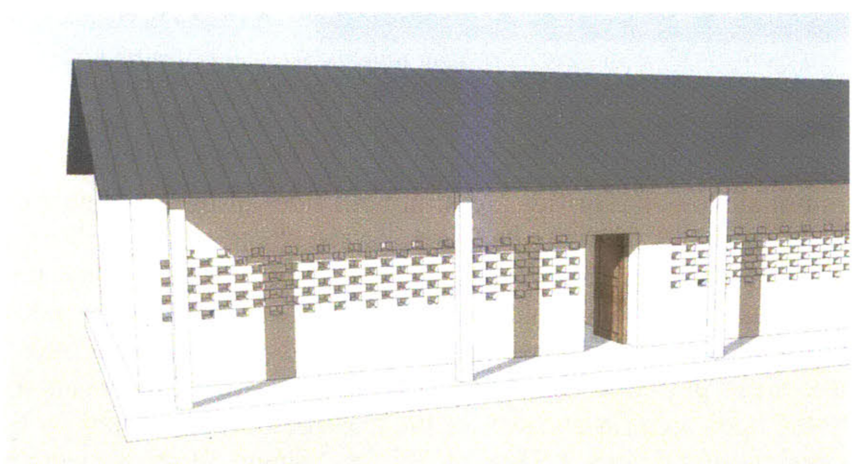


Figure 29: Rendering of the classroom with jali walls

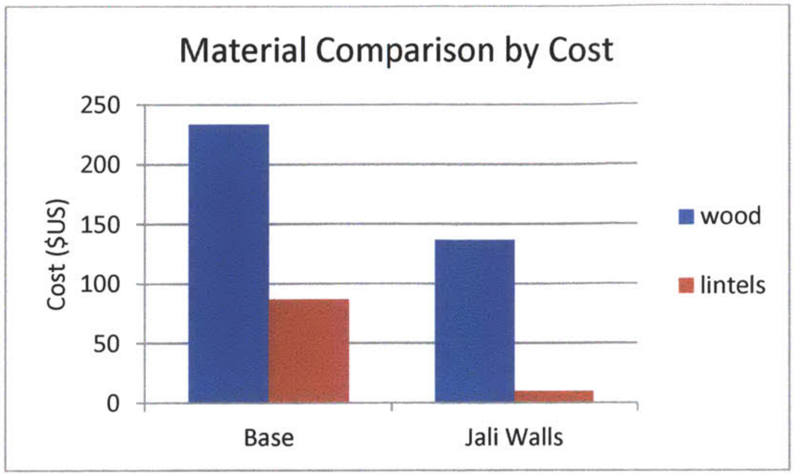


Figure 30: Material comparison between the base design and the jali wall design

Laurie Baker, who also researched pivoting shutters, did many buildings with jali walls in India. His sketches are seen in figure 32.

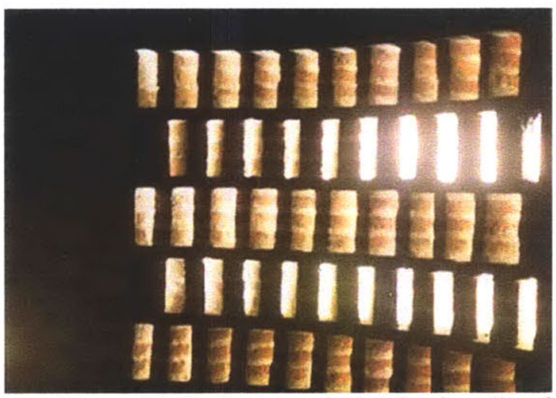
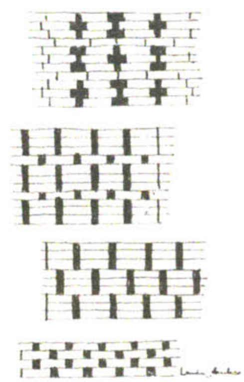



Figure 31-32: A photo of a brick jali wall and sketches by Laurie Baker

3.2.3 Five Windows

For maximum airflow, the orifice areas on both sides of the building should be equal. In the case of unequal openings, the smaller area, or the "bottleneck" will control the natural ventilation. Because the door may be left open during hot periods of the day, this means that the front of the building has additional open area, despite an equal number of windows on each side. To offset this, the total area of the base-design windows were divided into five equal sized windows and three were placed at the rear side of the classroom to create the five windows design. Therefore the open area on one side of the classroom in $3.8m^2$ and on the other side 4.2 $m.^2$ For the base design, this ratio is 3.52 m^2 to 5.52 $m.^2$ Figure 33 shows a rendering of the rear of the classroom as well as floor plans comparing the five window design to the base design.

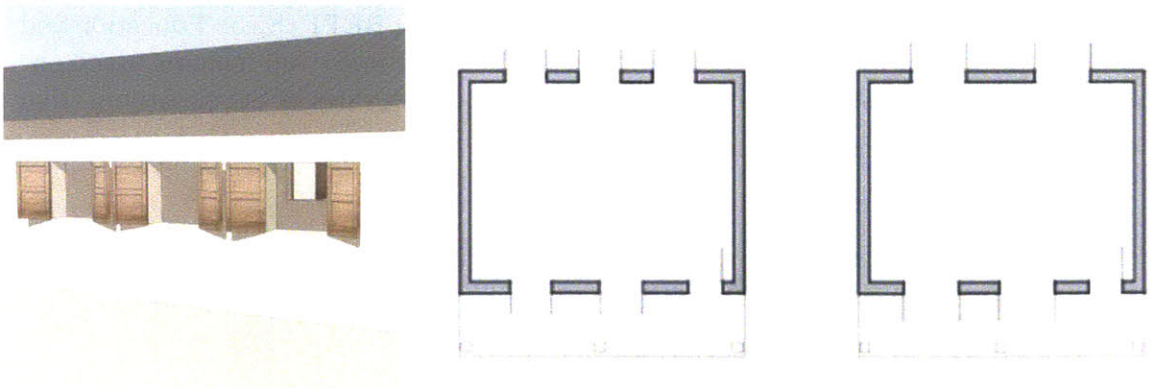


Figure 33: Rendering of the rear of the classroom and floor plans comparing the five window design to the base design

3.3 Roofing: The extended roof overhang

The rear of most classrooms in Sierra Leone have very short roof overhangs. While the front of the building is shaded from rain and direct sunlight because of the large porch, the rear of the building has very little protection from the elements. Therefore, a long roof overhang provides some of the same benefits as window protections, such as the awning shutters described in section 3.1.2. For example, when it is raining, the rear windows often have to be closed, and therefore very little light can enter the classroom. With a longer overhang, this problem can be avoided for most rains. For many classrooms, the rear is used as an access way. With a long roof overhang, this design can provide a shaded social space as well.

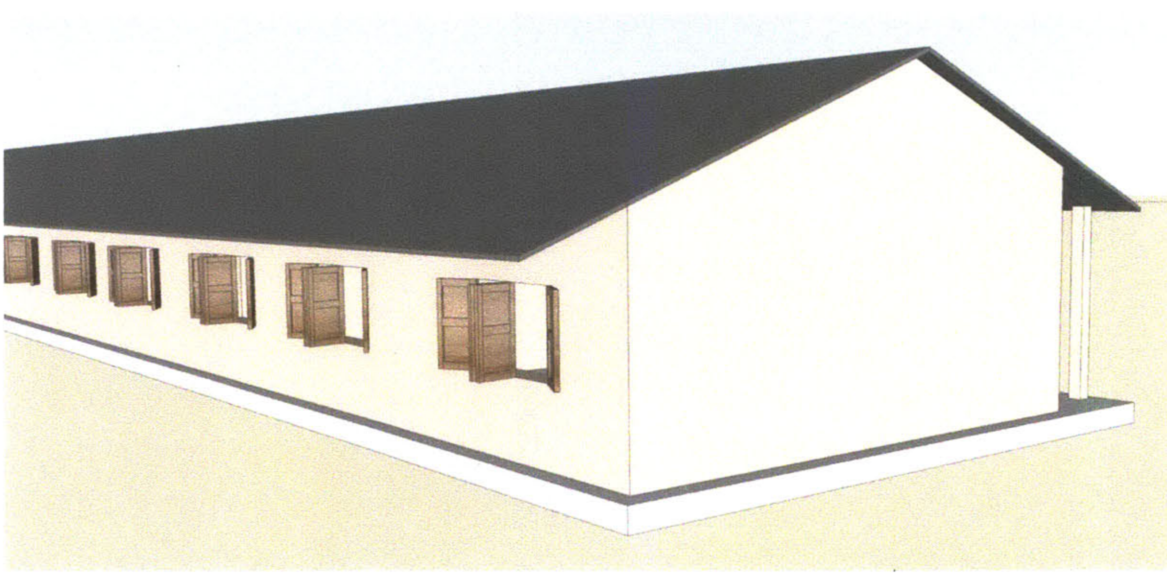


Figure 34: Model rendering with a 1.5 m roof overhang on both sides of the classroom

One example of extended roof overhangs is seen in the non-profit BETT (Basic Education and Teacher Training), who have built schools in Southeast Asia with improved features based on user evaluations. These schools use a 1.9 m roof overhang on both sides of the classroom (figure 35).

Figure 35:BETT School roof with a 1.9 m overhang

Chapter 4

Daylighting

The daylight analysis conducted for this report uses Lightsolve, a simulation program developed by MIT's Building Technology Department. This program gives a visual map that displays the percentage of interior light values, measured in lux, that are within the optimal range (300-800 lux). Lightsolve is a plugin for Google Sketchup, and therefore all models for this program are made in this program (Google Sketchup Pro, 2011).

To measure the illuminance, five sensor planes are placed in each classroom (figure 2). The normal vectors of each sensor point upwards in the direction that illuminance is measured. Two glare sensors are represented by two-dimensional vertical planes. One glare sensor is placed at both the front and the rear of the classroom and faces towards the center of the room to represent the directions a student or teacher would be facing. The glare is measured by total percentage of "discomfort glare," or DGP. All sensors are transparent and invisible. These sensors measure the illuminance or glare over the surface, but they do not block light.

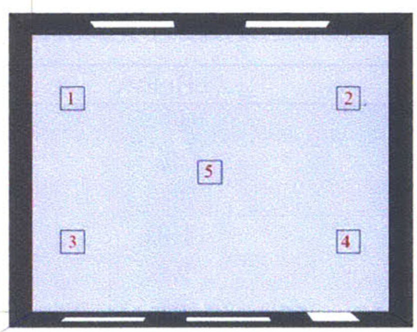
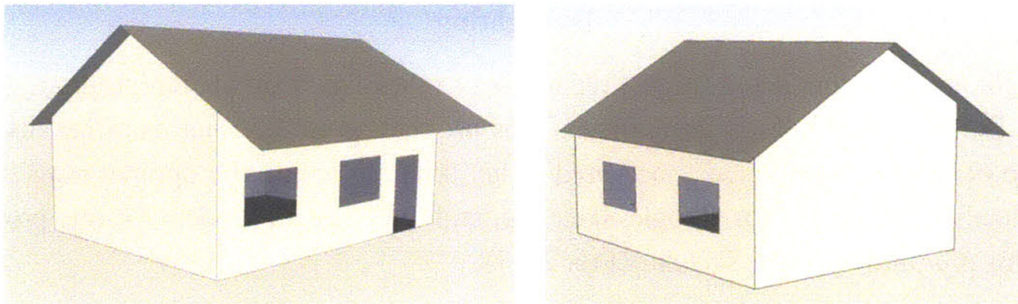


Figure 35: The placement of the five illuminance sensors used to gauge the daylighting performance of different classroom design.

4.1 The Base Design



Figures 36 & 37: Front and rear view of the base lighting model

Illuminance sensors are placed in five spots throughout the classroom. Sensor positions remain constant for all designs. The lowest levels of in-range illuminance are located at sensors 1 and 2, which are placed at the rear side of the classroom. This is because a greater percentage of lighting in these areas is at above-range levels compared to the other sensors. An average of 76% of the total illuminance levels meet lighting goals. The lighting is above range 15% of the school day (9 a.m.-5 p.m.) and below range 9% of the day. Glare levels are highest at the sensor closer to the door (24% GDP).

	At	Below	Above
Sensor 1	70%	9%	21%
Sensor 2	66%	7%	27%
Sensor 3	83%	9%	8%
Sensor 4	82%	10%	8%
Sensor 5	78%	10%	12%
AVERAGE	76%	9%	15%

Table 3: Illuminance measurements for the base design at five sensor points

	DGP
Glare 1	24%
Glare 2	20%

Table 4: Glare levels at the front of the classroom (Glare 1) and at the rear of the classroom (Glare 2).

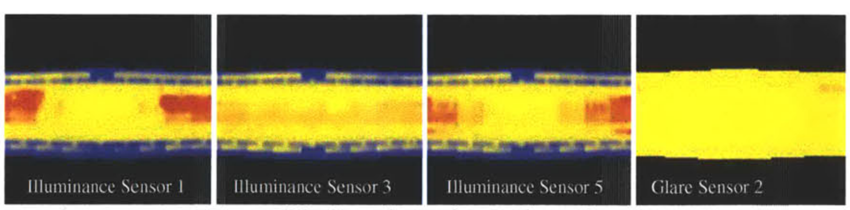


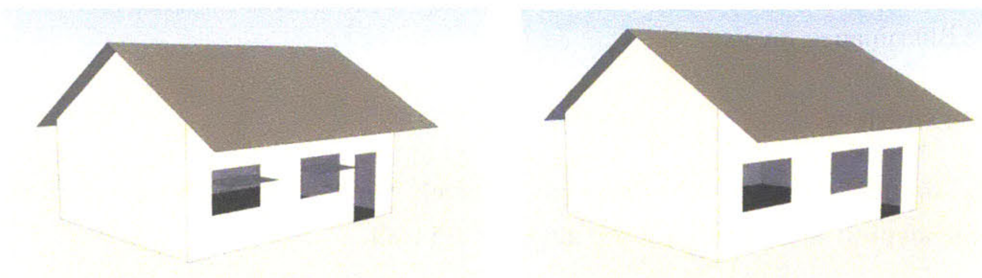
Figure 38: Sun charts for the base design

Sun charts showing the amount of light in-range (yellow), above-range (red), and below-range (blue) through the course of one year. Each alternative design is compared to these base design results. The vertical axis represents the time of day and the horizontal axis represents the time of year.

4.2 Shading

4.2.1 Pivoting shutters

This alternative design has pivoting shutters while the base design is simulated with no shutters to represent open casement shutters.



Figures 39 & 40: Pivoting shutter design compared to the base design (front views)

Compared to the base design, a greater percentage of in-range illuminance levels were found with the pivoting-shutter design (81% vs. 76%). However, a greater percentage of below-range levels were also present.

	At	Below	Above
Sensor 1	76%	17%	7%
Sensor 2	77%	15%	8%
Sensor 3	86%	12%	2%
Sensor 4	83%	17%	0%
Sensor 5	81%	17%	1%
AVERAGE	81%	16%	3%

Table 5: Illuminance measurements for the pivoting shutter design at five sensor points

The lighting simulations show that the pivoting shutters have very little effect on glare levels (table 6). The open doorway is the most likely cause of high glare levels at sensor 1, which is the same in the base design.

	DGP
Glare 1	24%
Glare 2	19%

Table 6: Glare levels at the front of the classroom (Glare 1) and at the rear of the classroom (Glare 2)

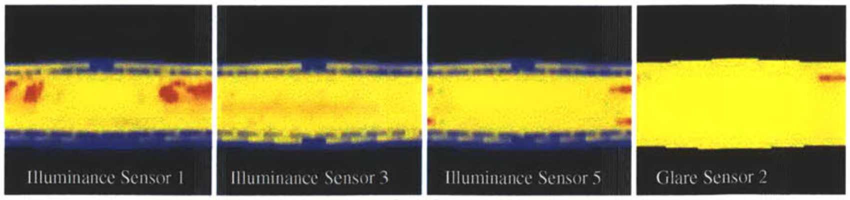


Figure 41: Sun charts for the pivoting shutter design

The sun charts for the pivoting shutters (figure 41) are compared to the sun charts for the base design (figure 38). The quantitative results are reiterated here: more yellow and blue represents a greater amount of light within-range and below-range; less red represents a smaller proportion of above-range illuminance levels.

4.2.2 Awning shutters

The awning shutter design uses planes above each window to represent the shutters. For simplicity, the awning shutters stay at 90° angle to the wall.

Figures 42& 43: Pivoting shutter design compared to the base design (front views)

A very similar percentage of in-range illuminance levels were found with the awning shutter design compared to the base design (77% vs. 76%). However, a much lower amount of above-range lighting was found in this design (2% vs. 15%).

	At	Below	Above
Sensor 1	72%	24%	4%
Sensor 2	73%	22%	4%
Sensor 3	83%	17%	0%
Sensor 4	79%	21%	0%
Sensor 5	78%	22%	0%
AVERAGE	77%	19%	2%

Table 7: Illuminance measurements for the pivoting shutter design at five sensor points

	DGP
Glare 1	25%
Glare 2	17%

Table 8: Glare levels at the front of the classroom (Glare 1) and at the rear of the classroom (Glare 2)

While glare in the rear of the classroom was reduced, the glare in the front of the classroom unexpectedly increased (table 5).

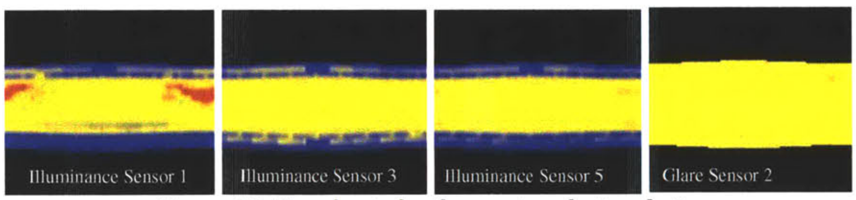


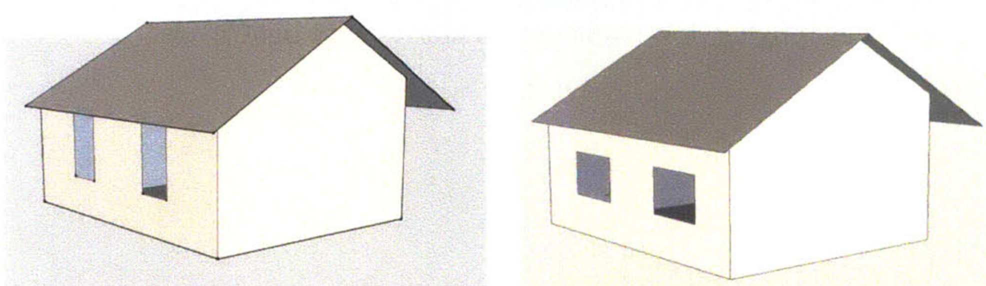
Figure 44: Sun charts for the awning shutter design

The sun charts for the awning shutters (figure 44) are compared to the sun charts for the base design (figure 38). Similar to the pivoting shutters, more yellow and blue represent a greater amount of light within-range and below-range; less red represents a smaller proportion of above-range illuminance levels.

4.3 Windows

4.3.1 Elongated windows

The elongated windows design lighting model has narrower, but taller, windows compared to the base design.


Figures 45 & 46: Pivoting shutter design compared to the base design (rear views)

Slightly higher levels of light at within-range illuminance were seen in the long window design (78% vs. 76%). Overall, these levels are very positive compared to the base design because the amount of above-range illuminance was also decreased (10% vs. 15%), but the amount of below-range illuminance did not increase by much (12% vs. 9%).

	At	Below	Above
Sensor 1	75%	14%	11%
Sensor 2	69%	10%	20%
Sensor 3	85%	12%	3%
Sensor 4	84%	12%	4%
Sensor 5	76%	13%	11%
AVERAGE	78%	12%	10%

Table 9: Illuminance measurements for the elongated window design at five sensor points

The glare levels decreased slightly overall by one percent DGP at each sensor.

	DGP
Glare 1	23%
Glare 2	19%

Table 10: Glare levels at the front of the classroom (Glare 1) and at the rear of the classroom (Glare 2).

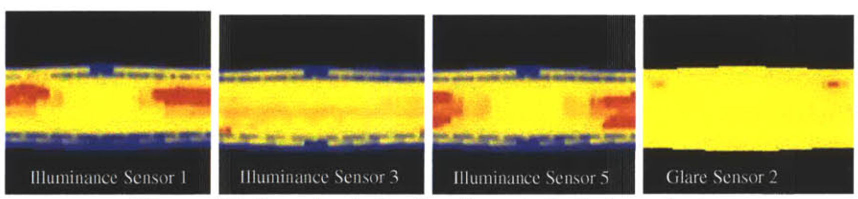
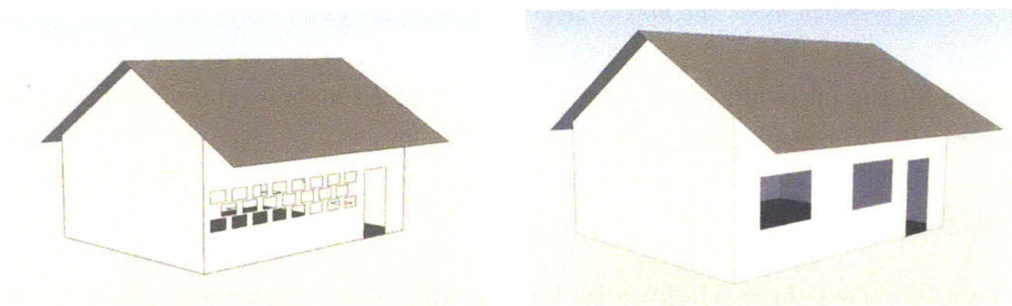


Figure 47: Sun charts for the elongated windows design

The sun charts show that all sensors have less above-range light levels than the base design, and that the glare levels have slightly lower amounts of above-range light levels.

4.3.2 Jali walls

The jali walls lighting model was simplified, ignoring wall thickness and using larger openings than real-life examples. The total open area for each model is the same, however.



Figures 48 & 49: Jali wall design compared to the base design (front views)

The lighting simulations showed that the jali wall design has less light at in-range levels and more light above-range. However, the model used for lighting was simplified, and real-work examples would have smaller openings and greater wall-thickness, which would have a large impact on results.

	At	Below	Above
Sensor 1	62%	6%	32%
Sensor 2	62%	6%	32%
Sensor 3	71%	6%	22%
Sensor 4	77%	9%	14%
Sensor 5	76%	10%	14%
AVERAGE	70%	7%	23%

Table 11: Illuminance measurements for the jali wall design at five sensor points

The amount of glare in the jali walls is slightly reduced from 20% to 19% in glare sensor 2.

	DGP
Glare 1	24%
Glare 2	19%

Table 12: Glare levels at the front of the classroom (Glare 1) and at the rear of the classroom (Glare 2).

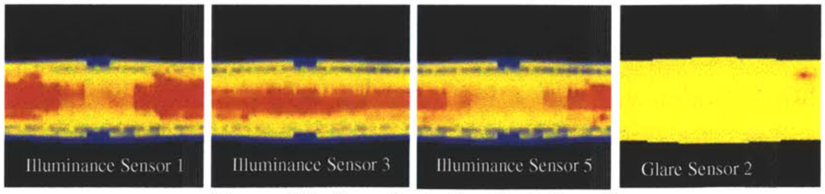
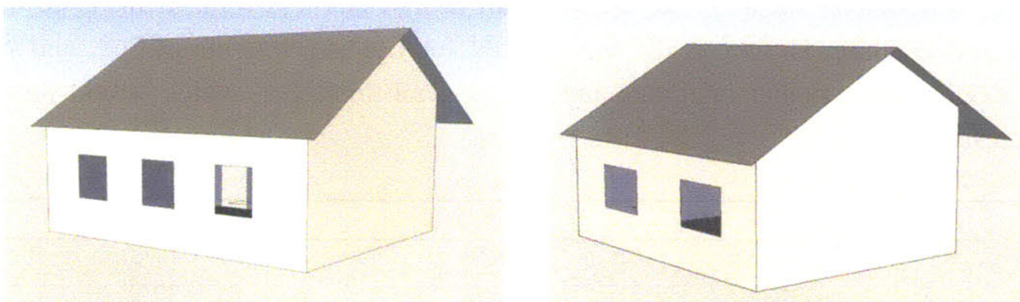


Figure 50: Sun charts for the jali wall

The sun charts for the jali walls have much more red in all sensors—showing the increased light at the above-range illuminance levels.

4.3.3 Five windows

The model above shows three windows on the rear side of the classroom. These three windows have a total open area of 4.2 m^2 compared to the base designs rear open area of 3.52 m^2



Figures 51 & 52: Five windows design compared to the base design (rear views)

The five window design received 4% more light than the base design in the above-range levels. This 4% was subtracted from the in-range levels, leaving the five window design with 72% and the base design with 76%. These results show the importance of having shading protection in the rear of the classroom, as sensors 1 and 2 at the rear of the classroom are receiving high levels of above-range lighting.

	At	Below	Above
Sensor 1	62%	5%	33%
Sensor 2	59%	5%	36%
Sensor 3	81%	10%	9%
Sensor 4	82%	11%	7%
Sensor 5	77%	12%	11%
AVERAGE	72%	9%	19%

Table 13: Illuminance measurements for the five window design at five sensor points

Slightly lower glare levels are seen in the rear of the classroom in the five window design.

Slightly lower glare levels are seen in the rear of the classroom in the five window design.

	DGP
Glare 1	24%
Glare 2	19%

Table 14: Glare levels at the front of the classroom (GLARE 1) and at the rear of the classroom (GLARE 2).

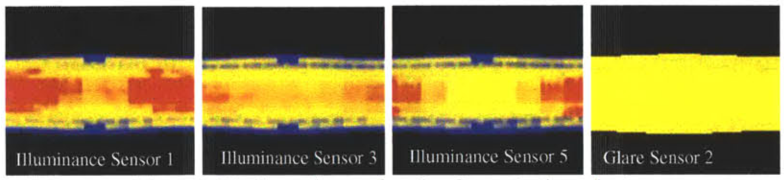
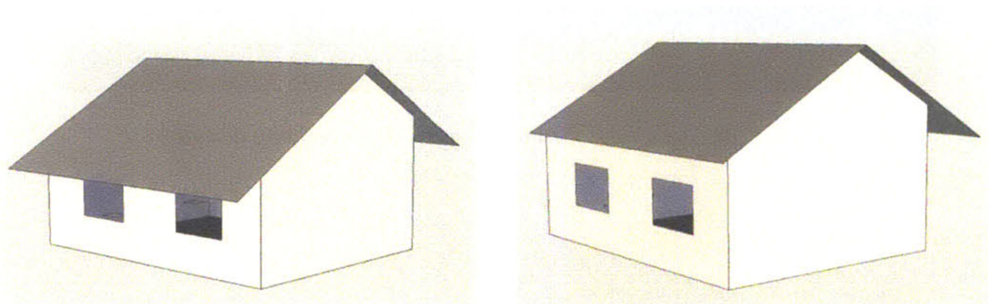


Figure 53: Sun charts for the five window design

The sun charts for the five window design (figure 53) show a greater amount of above-range lighting (red), especially in sensor 1, the sensor placed at the rear side of the classroom.

4.4 Extended roof overhang

The roof element was the only characteristic changed from the base design to the extended roof overhang design. Rather than a 0.5 m overhang on the rear side of the classroom, the extended roof overhang protrudes 1.5 m past the wall (figure 54). With a 30° roof angle, the horizontal difference is 0.7 m.



Figures 54 & 55: Extended roof overhang design compared to the base design (rear views)

The lighting simulation performed with the extended roof overhang resulted in an average of 5% more light at optimal levels relative to the base design. However, the amount of light at below-range levels is higher by an average of 7%. The largest changes were seen at sensors one and two, which are placed at the rear of the classroom (table 15). Here, the above-range light levels decreased from 21% to 7% and 27% to 7% respectively. Because these sensors have the greatest amount of above-range light in the base design compared to the other sensors, this design alterations evens the distribution of light levels throughout the classroom.

	At	Below	Above
Sensor 1	74%	20%	7%
Sensor 2	77%	16%	7%
Sensor 3	85%	15%	0%
Sensor 4	86%	14%	0%
Sensor 5	84%	15%	1%
AVERAGE	81%	16%	3%

Table 15: Illuminance measurements for the extended roof overhang design at five sensor points

The amount of glare in the extended roof overhang is slightly reduced from 20% to 18% in glare sensor 2.

	DGP (%)
Glare 1	24
Glare 2	18

Table 16: Glare levels at the front of the classroom (GLARE 1) and at the rear of the classroom (GLARE 2).

The sun charts show that the extended rear overhang has very little light in the above-range values (red), with a significant portion of its light levels at-range (yellow).

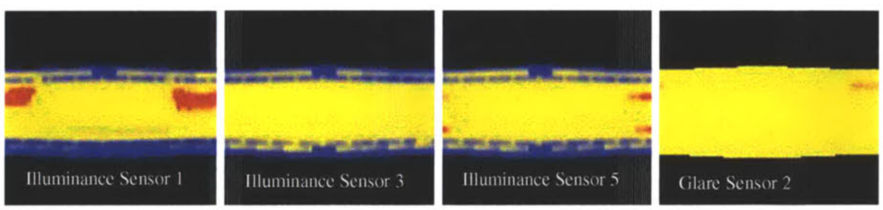


Figure 56: Sun charts for the extended roof overhang design

4.5 Summary

The results of the lighting simulations showed that some of the designs that were meant to shade the building--the awning shutters, the pivoting shutters, and the extended roof--succeeded in reducing illuminance levels that were above optimal (>800 lux). Unfortunately, these designs also resulted in a greater percentage of light below-range (<300 lux). With these designs, there is a trade-off between a greater percentage of below-range light levels and a greater percentage of in-range levels. However, the benefit of rain protection that these designs give may offset this. All together, the pivoting shutters and the extended roof give the best lighting results of the three shading designs (table 21).

Benefits of the shading devices:

- High levels of light at optimal range (300-800 lux)
- Very little light with above-range illuminance levels (>800 lux)
- Provide rain protection

Problems with the shading devices:

- Greater amount of light at levels below optimal range (<300 lux)

	At	Below	Above
Base	76%	9%	15%
Awning	77%	21%	2%
Pivot	81%	16%	3%
Extended Roof	81%	16%	3%

Table 17: The shading designs (awning and pivoting shutters as well as the extended roof overhang) increase both in-range illuminance levels and below-range levels.

The elongated window design also provides additional shading because a higher proportion of the open area is protected by the roof. Light levels improved overall, reducing the above-range illuminance levels and increasing the in-range illuminance levels (table 22). Unfortunately, this design still does not provide full rain protection that the other designs give. This design does reduce material use though, and further research on the lighting conditions throughout the room should be conducted to ensure that narrower windows do not leave "dark spots" in areas of the classroom that are not tested.

	At	Below	Above
Base	76%	9%	15%
Long	78%	12%	10%

Table 18: Lighting conditions of the elongated window design compared to the base design

Finally, the five window design and the jali wall design need further research before drawing any light performance conclusions. For example, the five window design has more open area at the rear of the classroom, but does not provide additional shading. Therefore, light levels above-range increased substantially from the base design (23% vs. 15%).

Additionally, the jali wall model was greatly simplified to expedite simulation time. The model has no wall thickness and does not accurately depict the size of each opening. Therefore, with greater complexity and more research, greater accuracy can be achieved in the lighting simulation before drawing conclusions about the lighting quality of this design.

	At	Below	Above
Base	76%	9%	15%
Jali wall	70%	7%	23%
Five windows	72%	9%	19%

Table 19: Lighting conditions of the elongated window design compared to the base design

Chapter 5

Natural Ventilation

While maximizing the natural ventilation in any building can be useful for reducing energy consumption, the classrooms analyzed rely solely on natural ventilation. The natural ventilation is controlled by the pressure differential across the openings that connect the exterior environment to the interior of the classrooms. This pressure is caused by wind on the opening and by the temperature increase that exists inside the classroom, in the case of buoyancy forces. For modeling the airflow inside the classroom, CONTAM Multizone Analysis Software was used. To further understand the heat gain and thermal comfort in the classroom, DesignBuilder, a graphical user interface for EnergyPlus, was used.

With no mechanical cooling system, the overall design goal is to reduce interior temperature gain by allowing as much natural ventilation inside the classrooms as possible. When comparing the natural ventilation in different school designs, both wind-driven and buoyancy air flows were considered. Air flow modeling was calculated with CONTAM Multizone Airflow and Contaminant Transport Analysis Software.

5.1 CONTAM

5.1.1 Heat gains inside the classroom

The goal of this study is to determine how much the interior temperature of the classroom increases compared to the outdoor temperature during specific design conditions. In order to calculate the difference in temperature from the exterior (T_{out}) to the interior (T_{in}) of the classroom, the heat loads from occupancy and the solar heat gain are first calculated. After the total thermal heat gain from occupants and sunlight is calculated, the equation ($q = \rho \cdot C_p \cdot V \cdot \Delta T$) is rearranged to find the difference in temperature from outside to inside the classroom (ΔT). In this equation, ρ and C_p, both constants, representing the density of air (1.2 kg/m³) and the specific heat of air (1000 J/kg·K), respectively. V represents the volumetric flow in m^3/s and is calculated with the simulation program CONTAM (Walton and Dols 2003).

$$q_{tot} = \rho \cdot C_p \cdot V \cdot (T_{in} - T_{out})$$

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = \frac{q_{total}}{(1.2kg/m^3) \cdot (1000J/kg) \cdot V}$$

The first heat load calculated is that from occupancy. The sensible heat gain for adults while seated and doing very light work is approximately 120 Watts, while the amount of heat gained from a child is about 75% of that, or 90 W ("Cooling Load Calculation," 2008). This value is multiplied by the total number of people expected to inhabit the classroom at full occupancy to find the heat load from occupancy inside the classroom.

$$q_{occ} = 50(students) \cdot 90W + 1(teacher) \cdot 120$$

$$q_{occ} = 4{,}620W$$

The second heat load calculated is due to the sunlight on the roof and depends on the material properties of the roof and the amount of solar heat that hits the roof. The solar reflectance of an unpainted metal roof is approximately 64% of the total short-wave radiation (Parker et al., 2000 & CMRC, 2006). However, this amount decreases overtime, as the metal roof oxidizes. Using a slightly reduced estimate of 60% reflectivity, approximately 50% of the remaining heat leaves by convection and radiation from the lower surface and the other 50% leaves by convection and radiation from the upper surface. Therefore, a total of 20% of the total heat on the roof will be transmitted to the interior. The surface area of the roof on one classroom is 67.5 m^2.

$$q_{occ} = 50(students) \cdot 90W + 1(teacher) \cdot 120$$

$$q_{occ} = 4{,}620W$$

q_{solar} = peak solar heat on roof · surface area of roof · % heat transmitted inwards

$$q_{solar} = 1{,}000\,W/m^2 \cdot 67.5m^2 \cdot 20\%$$
$$q_{solar} = 13{,}500W$$

The total heat load (q_{total}), in Watts, is comprised of occupancy and solar heat.

$$q_{total} = q_{occupancy} + q_{solar}$$
$$q_{total} = 13{,}500W + 4{,}620W$$
$$q_{total} = 18{,}120W$$

A value of 1000 W/m^2 is used as the peak solar heat on the roof, and is a worst-case scenario. However, the value of 20% is very sensitive to the aging of the room, and may increase significantly if the roof is not maintained. For example, if the reflectivity of the roof decreases to 40%, the heat gain calculated will increase to 20,250 W. Therefore, it is important to maintain roof reflectivity—for example, with regular maintenance and cleaning or painting the roof white—in order to reduce the amount of heat transmitted into the classroom.

5.1.2 Calculating volumetric flow with CONTAM to find ΔT

Next, CONTAM Multizone Airflow and Contaminant Transport Analysis Software, developed by NIST, is used to measure wind-driven and buoyancy flows through the classroom. Table 5.1 shows the average wind speed of Lunsar, 4.16 m/s, that was used as the input speed for wind-driven flows (New, 2002). Table 5.2 shows the average monthly tables, and the average of these numbers was calculated as 25.3°C and imputed as the exterior air temperature. CONTAM takes into account that this measurement is taken at an elevation of 10m by multiplying this input by a coefficient of 0.6 for elevation and terrain because this measurement was originally taken at a weather station 10m above ground.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Wind speed (m/s)	4.46	4.27	4.47	4.48	4.94	4.48	4.47	3.99	3.93	3.34	3.51	3.63	**4.16**

Table 20: Average wind speed per month in Lunsar, Sierra Leone

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Temp. (°C)	26.7	27.6	27.7	27.1	25.4	24.4	23.6	23.5	24.0	24.4	24.3	24.9	**25.3**

Table 21: Average temperature per month in Lunsar, Sierra Leone

Input wind speed = 4.16 *m/s*

Adjusted wind speed: 4.16 · 0.6 = 2.50 *m/s*

Input temperature: 25.3 ºC

Other inputs, including window and wall height, classroom dimensions, building type, and location data, were also included in the simulation inputs. All windows are placed 1.1 m above ground level and have a total area of 7.04 m^2; the door is placed 0.1 m above ground level to account for the foundation.

With the model and climate information input to CONTAM, an approximate interior temperature is estimated to reflect temperature increases in the classroom. Once CONTAM outputs a volumetric flow rate, the interior temperature is changed to reflect the differences between the calculated interior temperature (using the thermal comfort equation $q = \rho C_p V \cdot \Delta T$). The interior temperature is then changed to reflect these differences in an iterative process until the values match. Therefore, the final change in temperature is used by combining the results of CONTAM and the thermal heat loads calculated above.

Two types of flow paths are modeled in CONTAM: "orifice area" and "two-way flow model." In the orifice area model, the area of each opening is most important, so that wind driven flows may be calculated. In the orifice area model, the interior temperature is set equal to the exterior temperature, and therefore buoyancy flows are not accounted for. In the "two-way flow model," the elevation of the flow path is important input data to calculate buoyancy flows. Each model is run with buoyancy-only flows (0 m/s wind speeds) and two-way flow model with a 4.16 m/s wind speed (buoyancy and wind-driven flows added together).

5.1.2.1 Wind-driven flows in the "Base" design

First, the airflow through this classroom with only wind-driven flows was assessed. The base model has two windows on the front and rear side as well as a 1m x 2m door on the front side (figure 57).

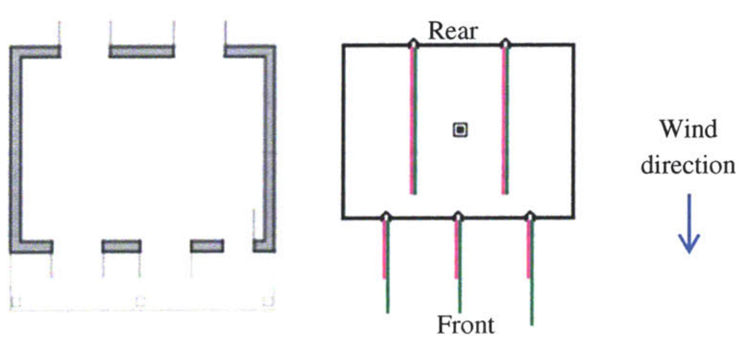


Figure 57: Floor plan of base design compared to CONTAM airflow model

The air change rate of the base design (wind-driven flows only) was found to be 4.36 air changes per hour (ACH) and the change in temperature was found to be 1.40 K. Both the exterior temperature and interior temperature was set at 25.3 °C, and therefore buoyancy flows are not considered in this model.

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / (1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 5.40 \text{ m}^3\text{/s})$$

$$\Delta T = 2.79 \text{ K}$$

5.1.2.2 Buoyancy-only flows in the "Base" design

Buoyancy flows were then calculated on the base design with two-way flow models for the windows and 0 m/s wind speed. With no wind, the air changes per hour were 0.59 and the change in temperature from the outside to the inside of the classroom was 10.34 K.

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / (1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 1.46 \text{ m}^3\text{/s})$$

$$\Delta T = 10.34 \text{ K}$$

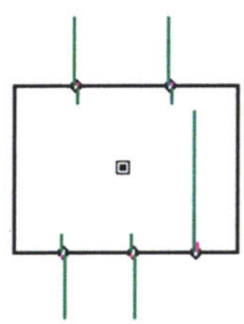


Figure 58: CONTAM airflow results for two-way buoyancy flows in the base model.

5.1.2.3 Buoyancy and wind-driven flows in the "Base" design

When wind speed is added to two-way buoyancy flows, the wind speed will cancel out some buoyancy flows going in the direction opposite of the wind. Additionally, different airflow models within CONTAM are used to measure wind-only airflow and two-way buoyancy airflows with wind speed. Therefore, the "wind" and "buoy & wind" measurements should not be compared directly to each other.

Buoyancy flows using a two-way flow model were then calculated with a 4.16 m/s wind speed. When wind speed was added to the simulation, the air changes per hour increased to 1.79 and the change in temperature dropped from 10.34 to 3.40 K. See Appendix II for iterations of the base design CONTAM model.

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / (1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.45 \text{ m}^3\text{/s})$$

$$\Delta T = 3.40 \text{ K}$$

Flow-type for BASE MODEL	Volumetric Flow (sm^3/s)	ACH	output ΔT (K)
Wind-driven	5.40	2.18	2.79
Buoyancy	1.46	0.59	10.34
Wind and Buoy	4.45	1.79	3.40

Table 22: Tabulated data for each airflow in the base model

5.1.2.4 The "five window" model

The base design—which has 2 windows on the rear side and 2 windows plus a door on the front side is next compared to a design with 3 windows on the rear side and only 2 windows (plus a door) on the front side (figure 59). The "5 windows" models takes the same total window area of the base design (7.04 m) and divides this amount between five equal windows—two in the front and three in the rear—of 1.4 m^2 each.

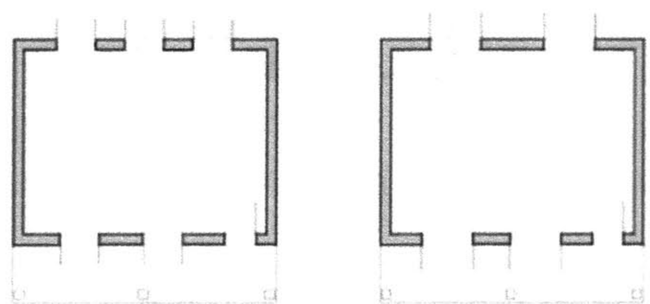


Figure 59: The "five window" model compared to the base design. Both models have equal total open area, but the 5 window model has one additional window in the rear.

While the airflow within the classroom will increase as window size increases, the openings on the front and rear side should be roughly equal size in order to maximize volumetric flow for a given opening area. Although both models have the same total window area, the "5 window" model has a greater effective area, as the front-side and rear-side orifice areas are closer to being equal.

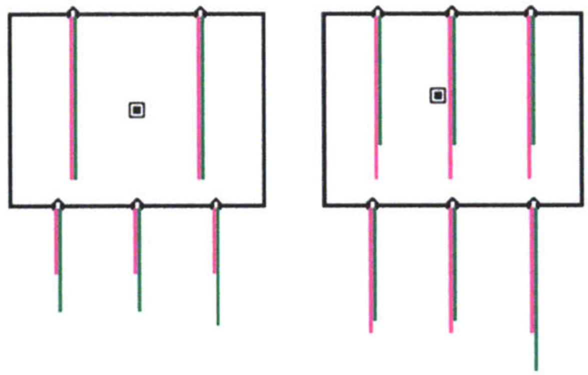


Figure 60: The base design compared to the "Five window" model in CONTAM for wind-driven airflows

The interior temperature difference between the 5-window design and the base design was small (0.2 K), but shows how airflow will increase if the orifice area on each side of classroom is closer to equal. Table 5 shows comparisons of airflow model for the base design and the five window design. See Appendix II for iterations.

Model type	**Air-flow type**	**Volumetric Flow (sm^3/s)**	**ACH**	**output ΔT (°C)**
Base	Wind-driven	5.40	2.18	2.79
5 Windows	**Wind-driven**	5.82	2.35	2.59
Base	Buoyancy	1.46	0.59	10.34
5 Windows	**Buoyancy**	1.46	0.59	10.34
Base	Wind and Buoy	4.45	1.79	3.40
5 Windows	**Wind and Buoy**	4.77	1.92	3.17

Table 23: Tabulated data for each airflow in the base model compared to the five window model

5.1.2.5 The "elongated windows" model

The wind-driven flows for the elongated window design are equal to those found in the base design (figure 61).

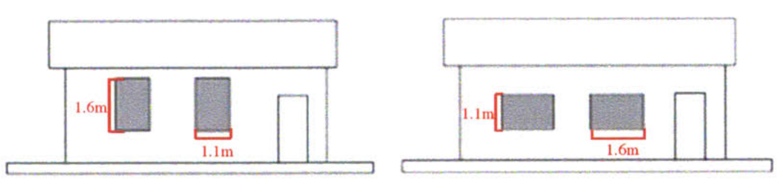


Figure 61: Elvation of the long window design compared to base window design

Therefore, buoyancy flows were next calculated for elongated windows using a 0m/s wind speed. With buoyancy-driven flows, the temperature inside the classroom was 1.19 K lower in the long-window design. See Appendix II for iterations.

Model Type for buoyancy flows	Volumetric Flow (sm^3/s)	ACH	output ΔT (K)
Base Model	1.46	0.59	10.34
Elongated windows	1.65	0.67	9.15

Table 24: Tabulated data for buoyancy airflows in the elongated windows model

5.1.2.6 The "rainy-weather" case

The last simulation was conducted with the rear two windows closed. Because there is a large front overhang (1.5 m), but not a large back overhang (0.5 m), the rear windows must be closed during heavy rains. This comparison acts as if pivoting or awning shutters, where the shutters provide rain protection or an extended roof overhang on the rear side of the classroom were added to the base design. Therefore, the base design (if altered with rain protection) is compared to the "rainy" condition, as if no alterations were made to protect from rain. When the rear windows are closed in the rainy condition, no wind-driven flow through the building can take place. As for buoyancy flows, the airflows are significantly decreased, raising the overall temperature 3.14 K. When wind is factored into the two-way flow model, the overall temperature raises 10.08 K (table 25). See Appendix III for iterations.

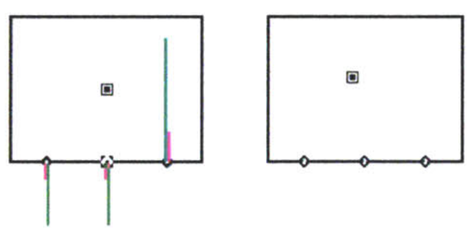


Figure 62: buoyancy and wind-driven CONTAM models in the "rainy-weather" case

Model type	Air-flow type	Volumetric Flow (sm^3/s)		output ΔT (K)
"Rainy" condition	**Wind-driven**	0	0	N/A*
Rain Protection Design	Wind-driven	5.40	2.18	2.79
"Rainy" condition	**Buoyancy only**	1.12	0.45	13.48
Rain Protection Design	Buoyancy only	1.46	0.59	10.34
"Rainy" condition	**Wind and Buoy**	**1.12**	**0.45**	**13.48****
Rain Protection Design	Wind and Buoy	4.45	1.79	3.40

*No wind-driven airflows are seen in the rainy-day wind-only model, therefore the output temperature cannot be calculated with the methods used in this report

**Because there are no wind-driven airflows in the rainy-day model, buoyancy flows stay constant when wind is added.

Table 25: Tabulated data for each airflow in the base model compared to the "rainy" model

5.1.3 Summary

The design goal in the CONTAM simulations is to get the change in temperature from outside the classroom to inside the classroom (ΔT) as close to zero as possible. The interior temperature inside the classroom is found using heat gain calculations and CONTAM outputs for airflow rate. The base, elongated windows, five windows, and the designs that give the classroom rain protection were all simulated. Two types of flow paths are modeled in CONTAM: "orifice area" and "two-way flow model." In the orifice area model, the area of each opening is most important, so that wind driven flows may be calculated. In the "two-way flow model," the elevation of the flow path is important input data to calculate buoyancy flows. Classroom features and climate data is also included.

CONTAM showed that the wind-driven airflows within the classroom are very important for natural ventilation. If the wind-speed is 0 m/s, and therefore only buoyancy flows are considered, the interior temperature of the base design is 10.34 K higher than the outdoor temperature. However, when wind was added to the buoyancy flows, ΔT was only 3.40 K.

The buoyancy flows increased in the elongated window design, decreasing the ΔT with 0 m/s wind from 10.34 K (base design) to 9.15 K. At such high temperatures, any increase in airflow is important. However, because the alteration is small, this difference is small. If the height of the windows were increased more, a greater change would be seen. Additionally, because the elongated windows are narrower, the number of windows could be increased, having a substantial effect of overall airflow.

When the orifice area on the rear side of the classroom nears a value equal to the front side, the wind-driven airflows increase, as in the case of the five window design. For wind-driven flows, the temperature difference between the base design model and the five windows model was 0.2 K. An improved design would combine these two effects, making the front and rear orifice areas equal, and elongating each window as well. The temperature differences would also increase as the scale of the difference increases—such as longer windows or equivalent orifice areas on the front and rear side.

The starkest contrast in ΔT was seen with the rear classroom windows closed, as would be the case in the base design during heavy rains. When the rear windows are closed, two-way flows through the building cannot occur, and the natural ventilation with any wind speed is 0 m/s when only considering wind-driven airflows. Therefore, only buoyancy flows affect this model. The difference in temperature between the base design when a rain protected design—such as the pivoting shutters, the awning shutters, and the extended rear overhang—is 3.14 K. The difference between a rain protected design and the long window design during rains is 4.33 K.

This significant change in temperature shows the benefit of having design alterations that allow the rear windows to stay open during rainy weather.

Model	Simulation Type	Volumetric Flow (sm^3/s)	ACH	output ΔT
BASE	Wind	5.40	2.18	2.79
BASE	Buoyancy	1.46	0.59	10.34
BASE	Buoy & wind	4.45*	1.79	3.40
LONG	Wind	5.40	2.18	2.79**
LONG	Buoyancy	1.65	0.67	9.15
LONG	Buoy & wind	3.41	1.78	3.41
FIVE	Wind	5.82	2.35	2.59
FIVE	Buoyancy	1.46	0.59	10.34
FIVE	Buoy & wind	4.77	1.92	3.17
RAINY	Wind	0	0	N/A***
RAINY	Buoyancy	1.12	0.45	13.48
RAINY	Buoy & wind	1.12	0.45	13.48****

*When wind speed is added to two-way buoyancy flows, the wind speed will cancel out some buoyancy flows going in the direction opposite of the wind. Additionally, different airflow models within CONTAM are used to measure wind-only airflow and two-way buoyancy airflows with wind speed. Therefore, the "wind" and "buoy & wind" measurements should not be compared directly to each other.
**long window design has same wind-driven flows as base design. This amount is affected by the size and distribution of windows on each side, factors which are equal in both designs.
***No wind-driven airflows are seen in the rainy-day wind-only model, therefore the output temperature cannot be calculated with the methods used in this report
****Because there are no wind-driven airflows in the rainy-day model, buoyancy flows stay constant when wind is added.

Table 26: Summary of all CONTAM simulations

5.2 DesignBuilder and EnergyPlus

DesignBuilder (2010) in combination with EnergyPlus (2010) was used to simulate the energy performance of the building over a typical year. The building geometry and simulation parameters were entered into DesignBuilder (figure 5), while EnergyPlus carried out the energy simulation using climate data from the closest available location—Accra, Ghana. The airflow that is modeled depends on this climate data as well as the building geometry and simulation inputs. All mechanical cooling, air conditioning, equipment, and lighting systems are turned off. Therefore, only natural ventilation is used to ventilate the classroom.

Some additional inputs include:

- An occupancy schedule that included 50 children inhabiting the classroom between
- 9 a.m. and 5 p.m.
- Building materials represent the classroom materials common to schools in Sierra Leone.
- The size, position, and location of each opening.
- Air changes per hour based on CONTAM simulations.

5.2.1 Extended Roof Overhang

First the base model was simulated to compare the effect of the roof. This effect is due to both the additional material insulation that the roof provides as well as the shading from the roof overhang. The average exterior dry-bulb temperature throughout the year was 26.9 °C. Table 27 shows the average temperatures and interior-exterior temperature differences for the base design with and without a roof. This is important to show the effect that the roof overhang has on shading. Next, the rear side of the roof on the base design model was increased from 0.5m to 1.5m to create the "extended roof overhang" model. The total temperature difference from outside the classroom to inside the classroom was 3.1 K (figure 63), a 1.2 K decrease from the base design. The total effect of the extended roof compared to having no roof at all was 2.6 K.

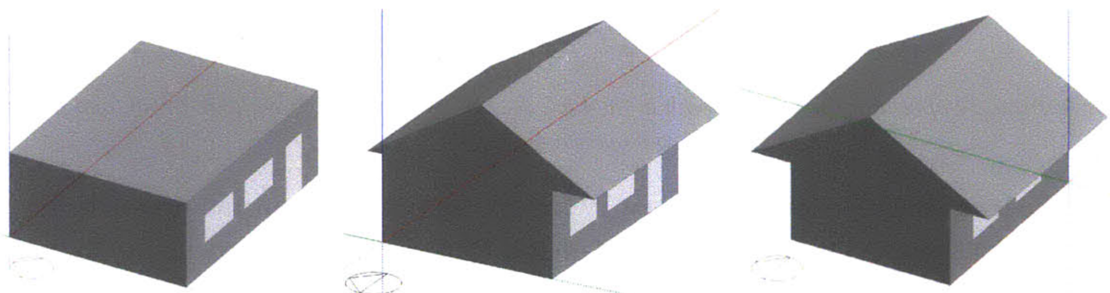


Figure 63: The three models—no roof, base, and extended rear overhang—compared first

Model and zone	Average Temperature (°C)	ΔT (K)
Base design	31.2	4.3
Base design without roof	32.6	5.7
Extended roof overhang	29.9	3.1

Table 27 Average Temperatures for the base design with and without a roof and with an extended roof overhang

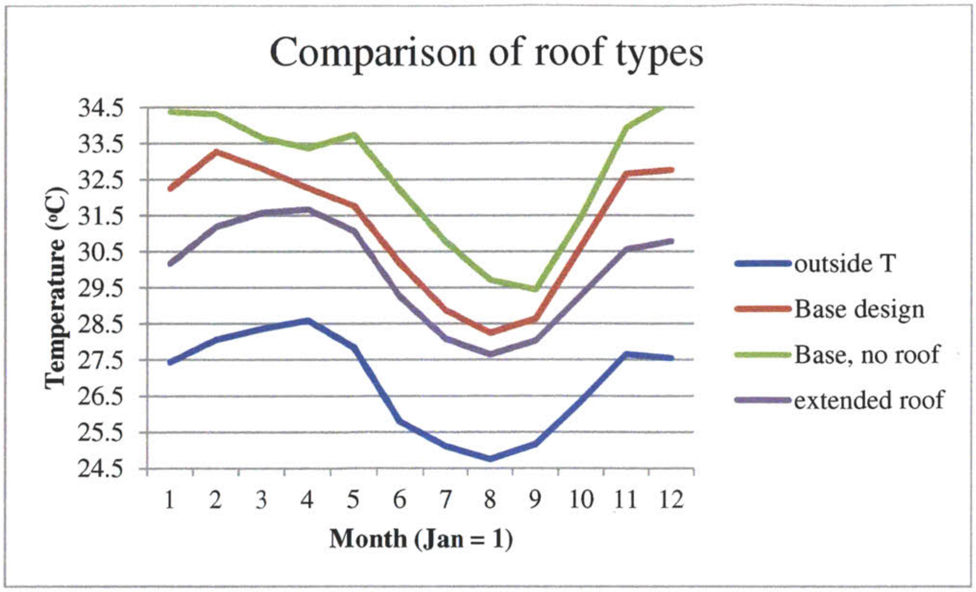


Figure 64: Average Temperatures for each month in the base design, the base design without a roof, and the extended roof overhang design

However, despite temperature averages between 29 and 33 degrees, the temperatures are much higher when only considering the hours between 9am and 5pm. Figure 5.9 shows hourly data for the operational period for the month of January.

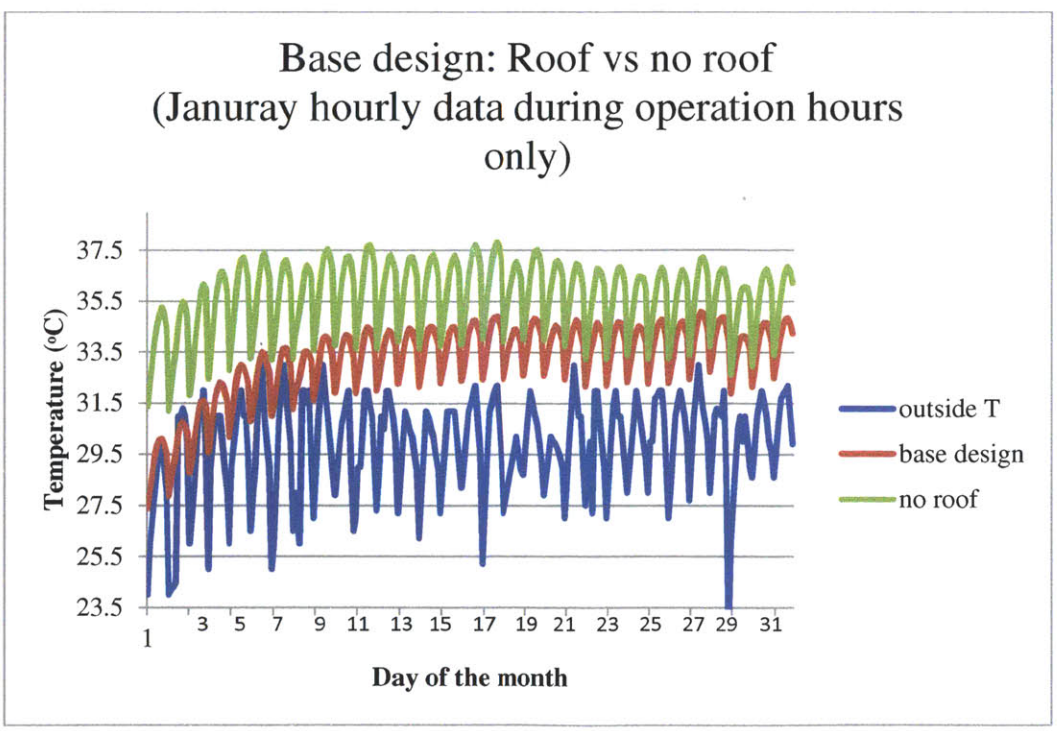


Figure 65: Hourly data for January 1st; Red lines mark 9am and 5pm, when temperatures are at the highest

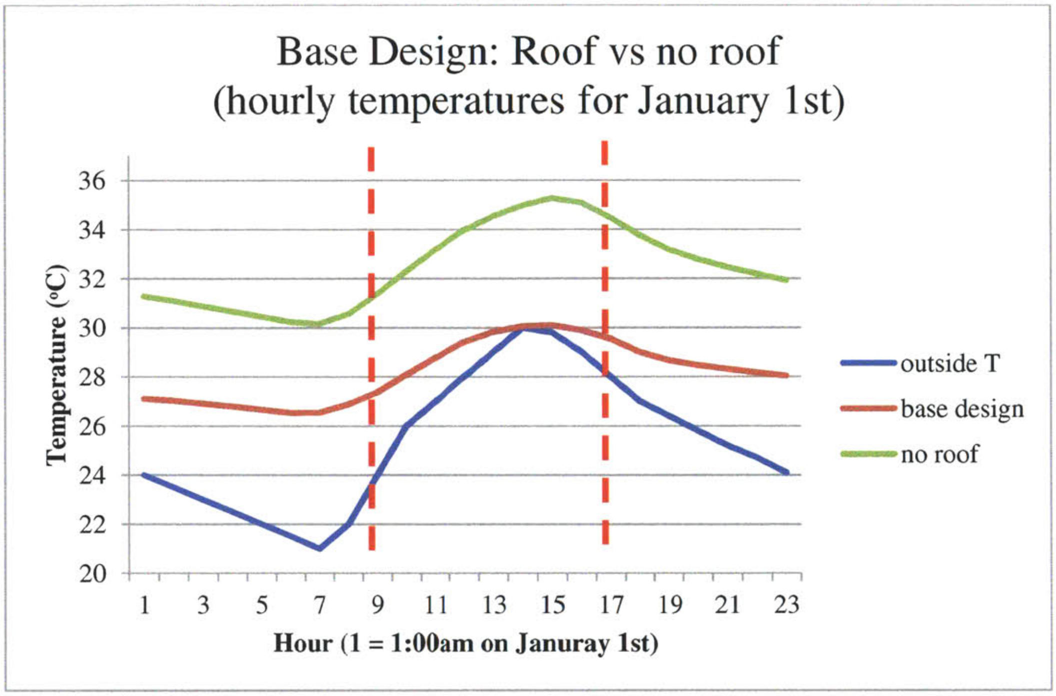


Figure 66: Hourly temperatures for January 1st graphed to show daily changes

5.2.2 Comparison of different shutter types

Shading devices, added to each window in the DesignBuilder model, were next compared to one another and the base design. The awning shutters and the sidefins both decreased the interior temperature averages throughout the year (figure 67). The pivoting shutters were modeled as a combination of interior and exterior shading, with a 0.66m extending outside the classroom at a 60° angle and 0.33m protruding inside the classroom at the same angle. This slanted angle had a significant impact on blocking heat gains inside the classroom compared to the other shading devices (table 28).

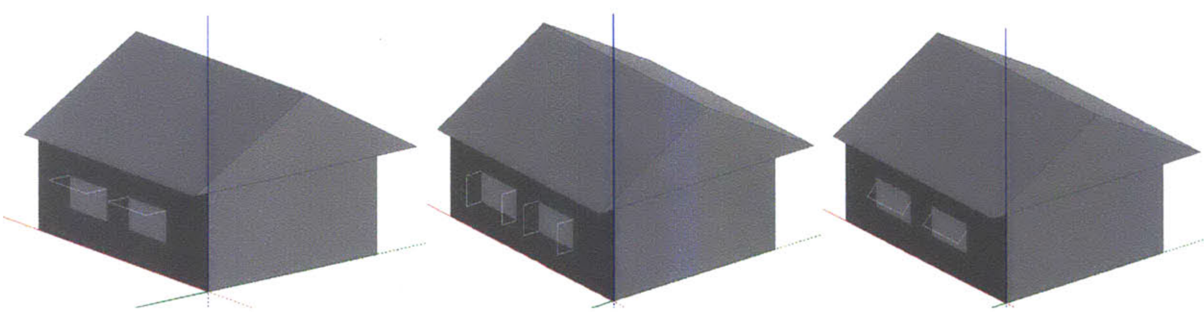


Figure 67: Awning shutters, sidefins, and pivoting shutters at a 60 degree angle were compared to the base design

Model and zone	Average Temperature (°C)	ΔT (K)
Base design	31.2	4.3
Base design with sidefins	32.6	3.7
Awning shutters	29.9	3.4
Pivoting shutters	28.7	2.2

Table 28: Average Temperatures for the base design compared to sidefins, awning, and pivoting shutters

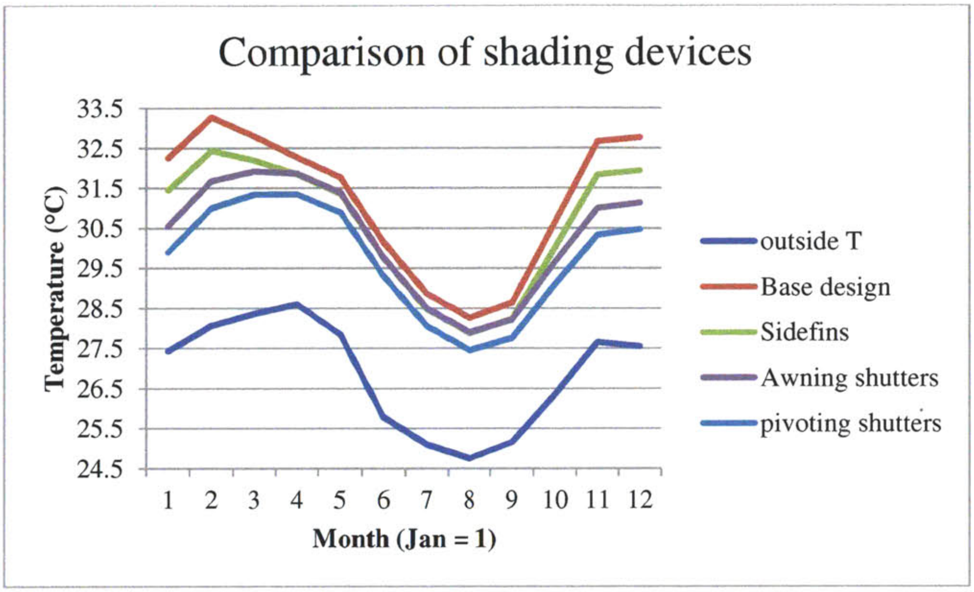


Figure 68: Average Temperatures for the base design compared to sidefins, awning, and pivoting shutters

5.2.3 Comparison of different window layouts

The base design was next compared to the five window design and the long window design. Figure 5.10 shows the comparison of each of these window layouts. The interior temperature of the five window design is 1 K lower than the base design (table 29).

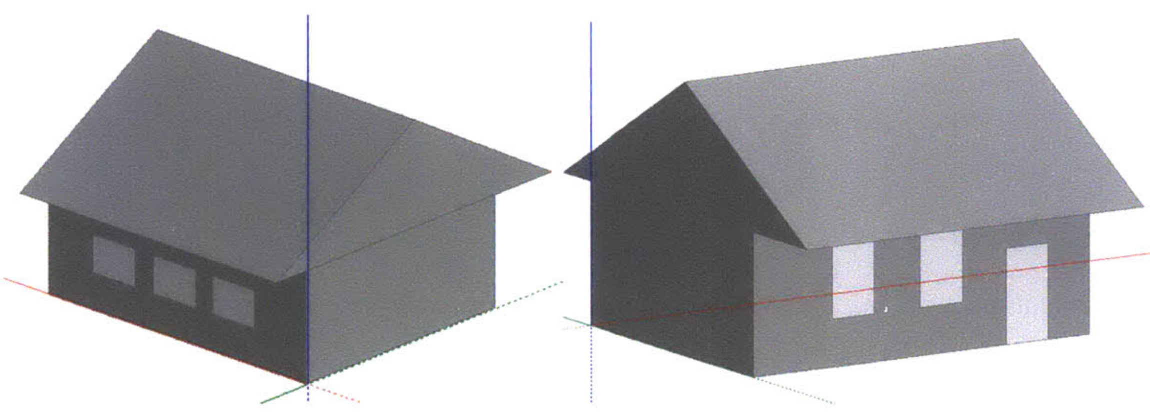


Figure 69: The five window design (left) and the long window design were compared to the base design

Model and zone	Average Temperature (°C)	ΔT (K)
Base design	31.2	4.3
Five windows	30.2	3.3
Long windows	31.0	4.2

Table 29 Average Temperatures for the base design compared to five windows and long windows

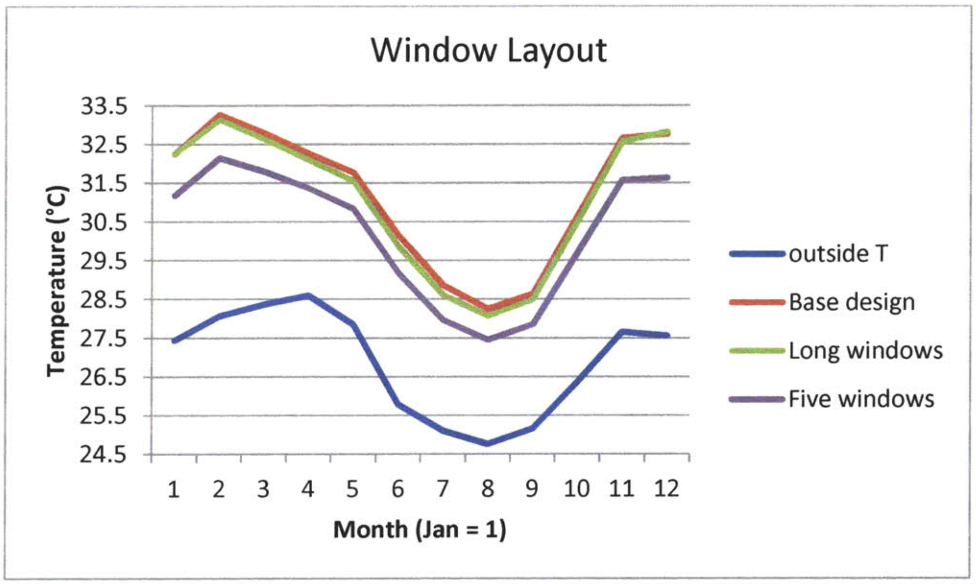


Figure 70: Graph of temperature differences between inside and outside the window layout designs

5.2 Summary

DesignBuilder (2010) in combination with EnergyPlus (2009) was used to simulate the overall thermal comfort of the building. Like CONTAM, the focus of these simulations was the difference in temperature from outside the building to inside the building (ΔT). Unlike the CONTAM results, EnergyPlus calculates the solar heat gain within the program. In the classroom simulations, all mechanical cooling, air conditioning, equipment, and lighting systems are turned off. The airflow that is modeled depends on climate data—such as average temperatures and wind speeds—from the region as well as the simulation inputs and the building geometry.

The most successful designs were the pivoting shutters, the extended roof overhang, and the five windows. The interior temperature of these designs increased 2.2-3.3 K relative to the outside temperature, compared with the base design's 4.3 K increase.

Model and zone	Average Temperature (°C)	ΔT (K)
Base design	31.2	4.3
Base design without roof	32.6	5.7
Extended roof overhang	29.9	3.1
Base design with sidefins	32.6	3.7
Awning shutters	29.9	3.4
Pivoting shutters	28.7	2.2
Five windows	30.2	3.3
Long windows	31.0	4.2

Table 25: Difference in temperature from outside to inside the classroom in all models

Chapter 6

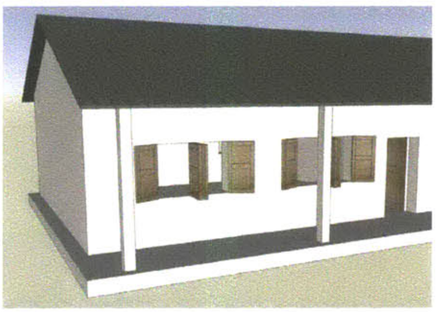
Design Report

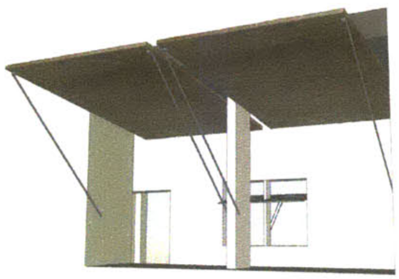
The cumulative results from all three simulation programs show the importance of shading the rear side of the building. The second most important element to be incorporated is equal amount of open area on each side of the classroom to increases airflow. All together, the most successful shading devices were the rear overhang and the pivoting shutters. The benefit of the rear overhang is that it would provide more overall protection for rain coming in at strong angles. However, precedent shows that pivoting shutters do not increase costs and may even reduce costs.

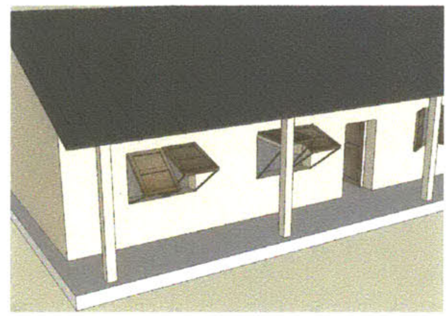
The following report gives an overview of classroom performance according to design, rather than simulation program. These were created as guidelines to reduce the risk associated with changing the current school designs.

Small scale designs for primary schools in Lunsar, Sierra Leone

May 2011







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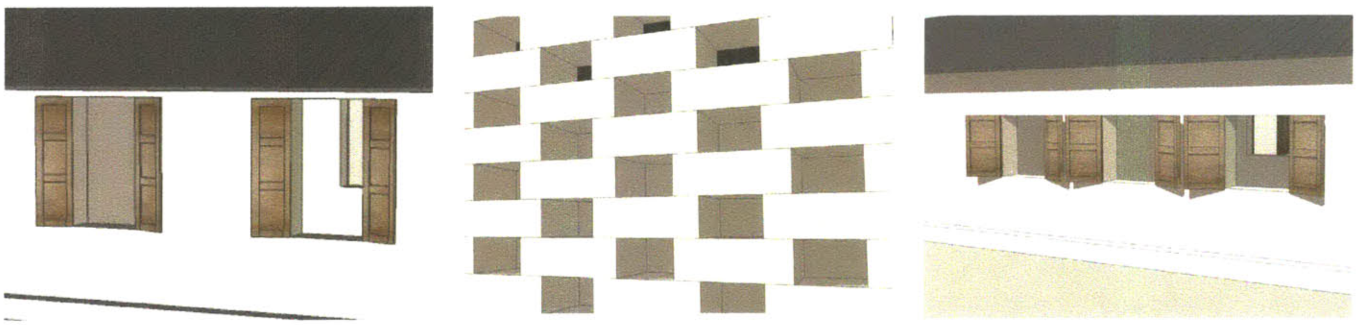
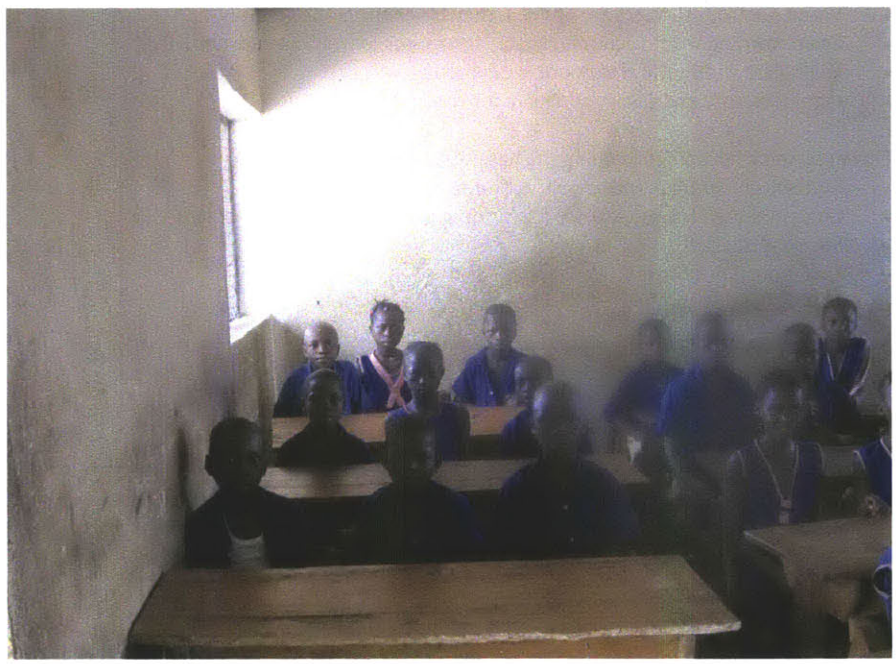


Introduction



Motivation

Most schools in Sierra Leone are constructed using a standard design with little variation from building to building. They are relatively high-cost and have poor ventilation, lighting and thermal comfort. In January 2010, thirteen primary schools in Sierra Leone were analyzed in order to identify design changes that will improve performance and reduce costs. One struggle that this analysis revealed is that construction methods have not changed for decades, as local builders resist changes in the current design. This guidebook aims to explain small-scale alterations for primary school buildings in Sierra Leone and list the impact on daylighting and thermal comfort performance for each alteration. For each design alteration, the daylight performance, air flow, and thermal comfort of the new design are compared to the standard design. The overall goal of these guidelines is to reduce the risk of design changes and improve the performance of schools without raising costs.

Introduction

Methodology

Six design alternatives were created based on problems identified during the analysis of current schools in the region. The performance of each alternative, in terms of lighting and ventilation, will be used to compare to the "base" design. While the average school size is six classrooms (figure 1), only one classroom will be used to compare each design. Some notable features that will be scrutinized in this report include the current casement shutters (figure 2) versus awning and pivoting shutters (figure 3), window layout, and roof shading. Only one variable changed from the base design at one time. For example, if the position of the windows is changed, the area of the window will remain the same. Therefore, the values calculated will be applicable without any other changes to the building.

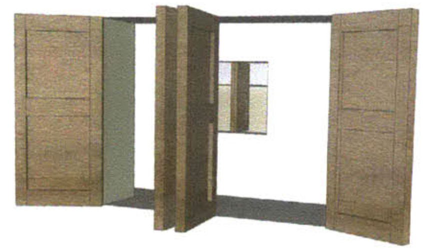


Figure 2: Detail of shutters from the base design

Below are some problems with the base design that the design alterations aim to address:

- Very little overhead protection from direct heat gains on the rear side of the building
- Shutters on the rear side of the building must be closed during rains
- When the front shutters are opened, they block the front pathway
- Overcrowding within schools causes classrooms to head up substantially
- High glare within the classroom is distracting
- Light levels are not always adequate for reading and writing

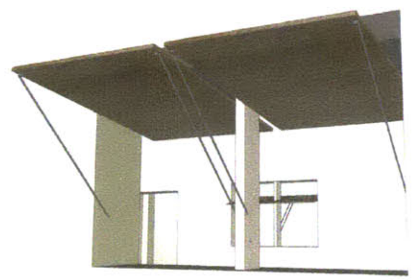


Figure 3: Example of one design alternative, pivoting shutters

However, some benefits to keeping the base design include:

- Builders are familiar with construction methods
- Current design is a safe choice for funding agencies and has precedent
- Local familiarity
- Tradition appearance

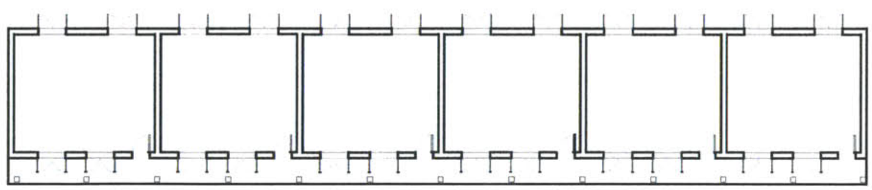


Figure 1: Floor plan of the base design

Daylighting

The daylight analysis in this guidebook uses Lightsolve, a simulation program developed by MIT's Building Technology Department. This program gives a visual map that displays the percentage of interior light values, measured in lux, that are within the optimal range (300-800 lux). All models for this program are made in Google Sketchup (Google Sketchup Pro, 2011).

To measure the illuminance, five sensor planes are placed in each classroom (figure 2). The normal vectors of each sensor point upwards in the direction that illuminance is measured. Two glare sensors are represented by two-dimensional vertical planes. One glare sensor is placed at both the front and the rear of the classroom and faces towards the center of the room to represent the directions a student or teacher would be facing. All sensors are transparent and invisible. These sensors measure the illuminance or glare over the surface, but they do not block light.

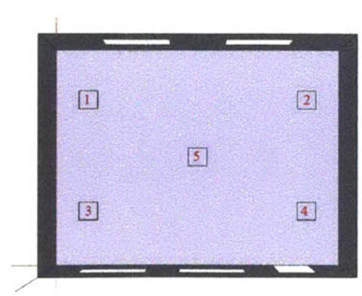


Figure 2: The placement of the five illuminance sensors used to gauge the daylighting performance of different classroom design.

Natural Ventilation

While maximizing the natural ventilation in any building can be useful for reducing energy consumption, the classrooms analyzed rely solely on natural ventilation. The natural ventilation is controlled by the pressure differential across the openings that connect the exterior environment to the interior of the classrooms. This pressure is caused by wind on the opening and by the temperature increase that exists inside the classroom, in the case of buoyancy forces. For modeling the airflow inside the classroom, CONTAM Multizone Analysis Software was used. To further understand the heat gain and thermal comfort in the classroom, DesignBuilder, a graphical user interface for EnergyPlus, was used.

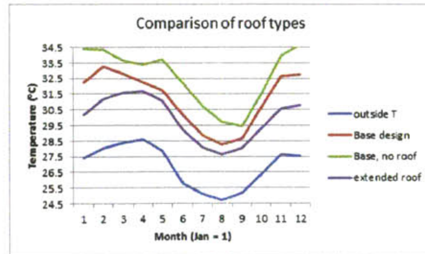


Figure 3: Comparing interior temperatures to exterior temperatures in classroom models with different roof types.

Air Flow

With no mechanical cooling system, the overall design goal is to reduce interior temperature gain by allowing as much natural ventilation inside the classrooms as possible. When comparing the natural ventilation in different school designs, both wind-driven and buoyancy air flows were considered. Air flow modeling was calculated with CONTAM Multizone Airflow and Contaminant Transport Analysis Software.

To obtain the change in temperature from outside the classroom to inside the classroom (ΔT), the total heat loads(q) from solar gains and occupancy gains were first calculated. The equation for thermal comfort, $q = \rho \cdot Cp \cdot V \cdot \Delta T$, was then used to determine the change in temperature given the volumetric flow rate output by CONTAM. The average wind speed of Lunsar, Sierra Leone (4.16m/s) was used to calculated the wind driven flows. The exterior temperature was set at the average, 25.3°C.

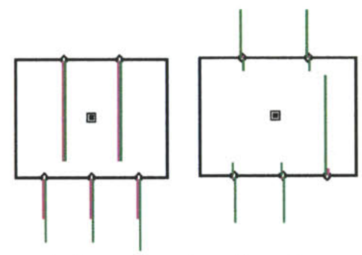


Figure 4: Example output from the simulation program CONTAM showing wind-driven and buoyancy airflows through a single classroom.

Thermal Comfort

DesignBuilder (2010) in combination with EnergyPlus (2010) was used to simulate the energy performance of the building over a typical year. The building geometry and simulation parameters were entered into DesignBuilder (figure 5), while EnergyPlus carried out the energy simulation using climate data from the closest available location—Accra, Ghana. The airflow that is modeled depends on this climate data as well as the building geometry and simulation inputs. All mechanical cooling, air conditioning, equipment, and lighting systems are turned off. Therefore, only natural ventilation is used to ventilate the classroom.

Some additional inputs include:

- An occupancy schedule that included 50 children inhabiting the classroom between
- 9 a.m. and 5 p.m.
- Building materials represent the classroom materials common to schools in Sierra Leone.
- The size, position, and location of each opening.
- Air changes per hour based on CONTAM simulations.

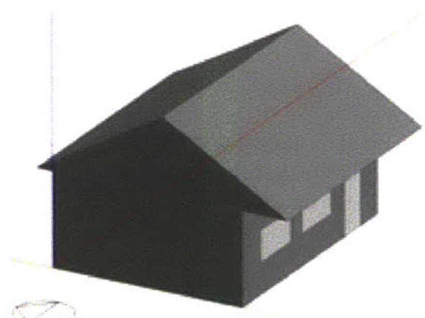
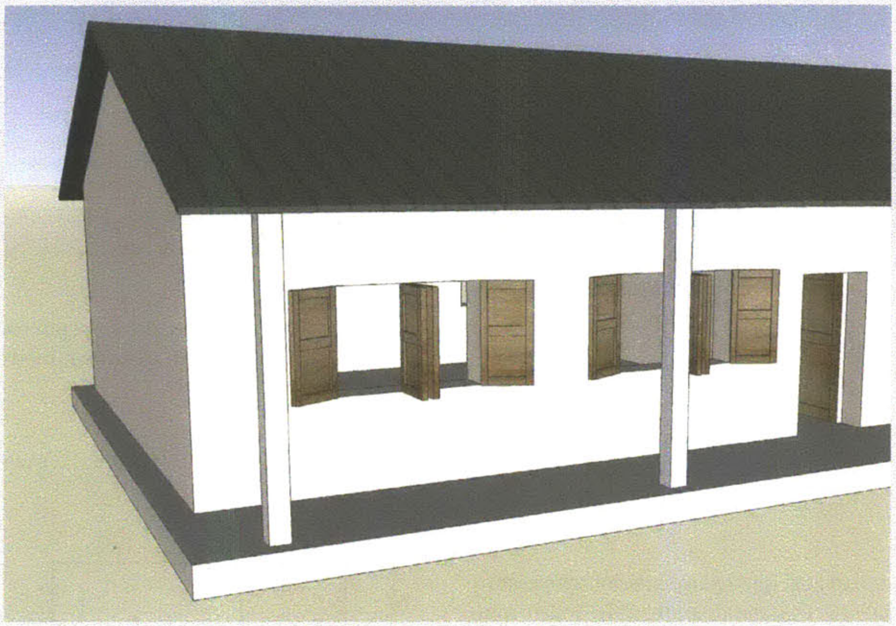


Figure 5: A model of the base design built in DesignBuilder, the an interface for EnergyPlus that was used to carry out energy simulations.

#1 Base Design



Design Overview

In the base design, each classroom is 6.1 m wide and 8 m long. There are four windows per classroom, each with an average area of 1.76 m^2, and beginning one meter from the foundation. Steel-reinforced concrete lintels span each window and the doorway. The walls are constructed of locally made soil or concrete bricks that are covered with a layer of stucco and paint. The roof on the base design extends over a front walkway 1.5 m, providing shade and rain protection. In the rear of the building, the roof overhang extends 0.5 m.

The benefits of base design are mostly due to local familiarity. This general design was introduced to Sierra Leone decade ago, and therefore is familiar to the culture and well-known to local builders.

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	70%	9%	21%
SENSOR 2	66%	7%	27%
SENSOR 3	83%	9%	8%
SENSOR 4	82%	10%	8%
SENSOR 5	78%	10%	12%
AVERAGE	**76%**	**9%**	**15%**

Table 1: An average of 76% of the total illuminance levels meet lighting goals. The lighting is above range 15% of the school day (9 a.m.-5 p.m.) and below range 9% of the day. A significant amount of the light that is above the upper-limit illuminance goals (800 lux) is located at sensors 1 & 2, which are located at the rear of the classroom. Glare levels are highest at the sensor closer to the door (24% GDP).

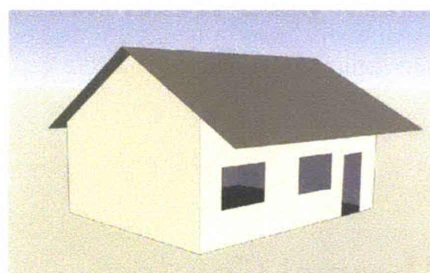


Figure 2: Illuminance sensors are placed in 5 spots throughout the classroom. Sensor positions remain constant for all designs. The lowest levels of in-range illuminance are located at sensors 1 and 2, which are placed at the rear side of the classroom. This is because a greater percentage of lighting in these areas is at above-range levels compared to the other sensors.

Annual Illuminance and Glare Charts: Base Design

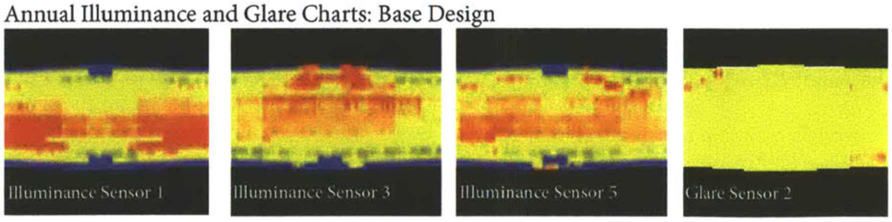


Figure 1. Sun charts showing the amount of light in-range (yellow), above-range (red), and below-range (blue) through the course of one year. Each alternative design is compared to these base design results. The vertical axis represents the time of day and the horizontal axis represents the time of year.

	DGP
GLARE 1	24%
GLARE 2	20%

Table 2: Glare levels at the front of the classroom (GLARE 1) and at the rear of the classroom (GLARE 2).

#1 Base Design

Materials[1]

Wood Shutters

Item	Quantity	Cost/Unit	Total Cost
1. Wooden Shutters	8	$12.13	$97.08
2. Lintels	4	$ 21.65	$86.61
3. Rebar	4	$ 91.02	$364.08
Total			**$547.76**

Masonry Walls[2]

Item	Quantity[3]	Cost/Unit	Total Cost
1. Masonry Walls	64.89 m^2	\$11.11/m^2	$721.04
Total			**$721.04**

Roofing

Item	Unit Cost	Quantity	Total Cost
1. Zinc Roof	80	\$5.89/m^2	$470.52
2. Wooden Trusses[4]	102	\$1.33/m^2	$136.52
Total			**$606.66**

Local familiarity with construction methods may allow cost reductions that are not included in material calculations, as the markets for the materials are established and building elements do not have to be particularly customized.*

*However, many elements, such as the wooden shutters are custom-made for each building, as the window sizes vary from building-to-building

Assumptions

1 The items included are only those that change during the course of this analysis. Items not included: foundation, porch, pillars, bond beam, furniture, doors, and contingency costs.
2 Included in the costs of the masonry walls are 7.5% cement mortar, 30% stucco, and 5% cement in mud brick blocks.
3 The quantity of masonry walls is measured in area (m^2), and the thickness of the walls (approximately 0.2 m) is consistent throughout the analysis
4 The wooden trusses are evaluated as 2 inch thick wood boards

Air Flow

The results in table 3 below show the airflow results for the "two-way flow" path that is modeled in CONTAM. This table lists the volumetric airflow rate, air changes per hour, and the output change in temperature (ΔT) that is calculated from a combination of thermal comfort analysis and CONTAM results. ΔT for buoyancy-only flows represents airflows with a 0 m/s wind speed. With outdoor dry-bulb temperatures averaging 25.3 °C, this temperature change is substantial.

When wind speed is added to two-way buoyancy flows, this wind speed will cancel out some buoyancy flows going in the direction opposite of the wind. Additionally, different airflow models within CONTAM are used to measure wind-only airflow and two-way buoyancy airflows with wind speed. Therefore, the "wind" and "buoy & wind" measurements should not be compared directly to each other.

Flow-type for the base model	V* (sm^3/s)	ACH**	output ΔT (K)
Wind-driven	5.40	2.18	2.79
Buoyancy flows	1.46	0.59	10.34
Wind and buoyancy	4.45	1.79	3.40

*Volumetric Air flow **Air changes per hour

Table 3: Volumetric flow, air changes per house, and temperature changes for different types of flow models in the base design.

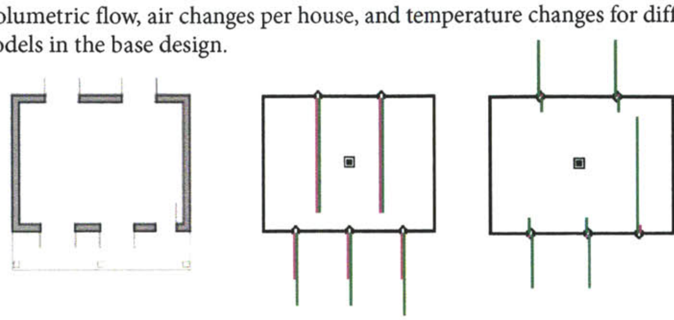


Figure 3: The floor plan (left) represented with the CONTAM visualization of wind-driven flows (center) buoyancy-driven flows (right).

Thermal Comfort

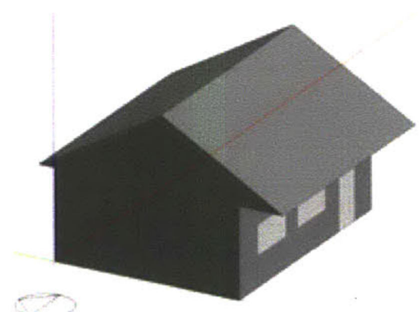
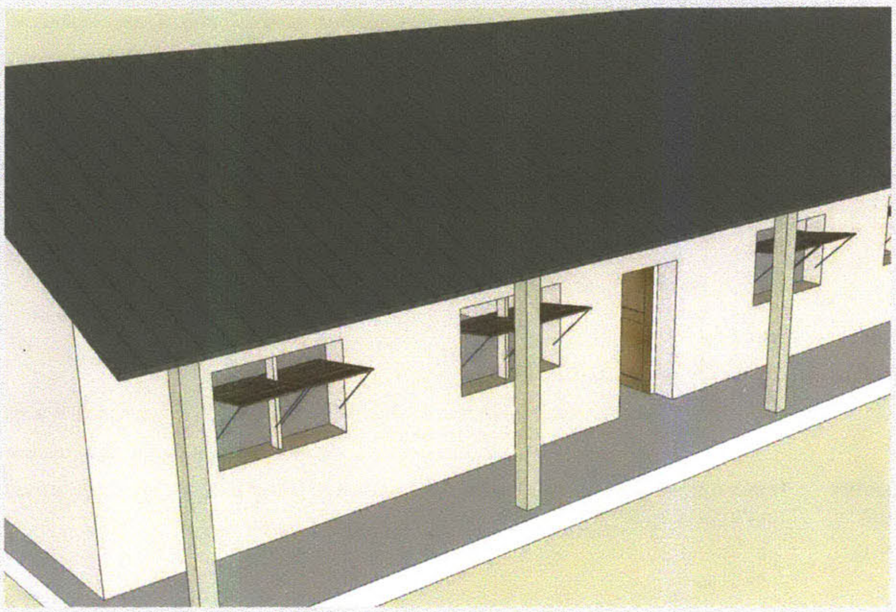


Figure 4: Model of the base design built in DesignBuilder for EnergyPlus simulations

In the EnergyPlus simulations, the exterior dry-bulb temperature was 26.9 °C. The base model built with DesignBuilder (figure 4) only represents one classroom. The simulation for the base design shows that the interior temperature is, on average, 4.3 K above the exterior temperature. This value is comparable with the CONTAM values, as slightly different climate data were used. Therefore, data from DesignBuilder/EnergyPlus should directly compared to CONTAM results.

Base Design	Average T (°C)
Interior Temperature	31.2
Exterior Temperature	26.9

#2 Pivoting Shutters



Design Overview

For the pivoting shutter design, the classroom dimensions, window size, and roof size do not differ from the base design. Shutters that pivot rather than open horizontally can be adjusted to any angle and are stabilized with props that attach to the window sill. The shutter design can be made with a range of materials types, including wood, metal, or fiberglass.

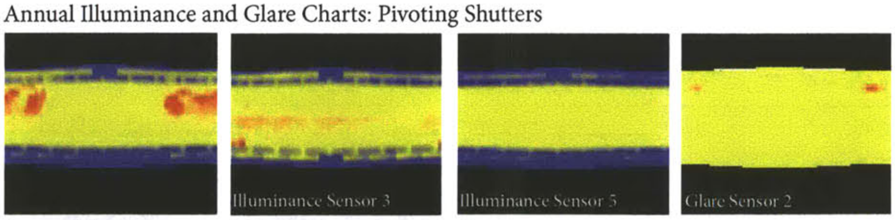
The most beneficial aspect to pivoting windows is being able to adjust the angle of the shutter depending on climate conditions. For example, in rainy weather, the shutters may be angled down to prevent water from entering the classroom. If fully opened, the shutters may act as a light shelf, allow light to reflect off the top of the shutter and penetrate deeper into the classroom.

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	76%	17%	7%
SENSOR 2	77%	15%	8%
SENSOR 3	86%	12%	2%
SENSOR 4	83%	19%	0%
SENSOR 5	81%	17%	1%
AVERAGE	**81%**	**16%**	**3%**

Table 4: Compared to the base design, a greater percentage of in-range illuminance levels were found with the pivoting-shutter design (81% vs. 76%). However, a greater percentage of below-range levels were also present.

Annual Illuminance and Glare Charts: Pivoting Shutters



Annual Illuminance and Glare Charts: Base Design

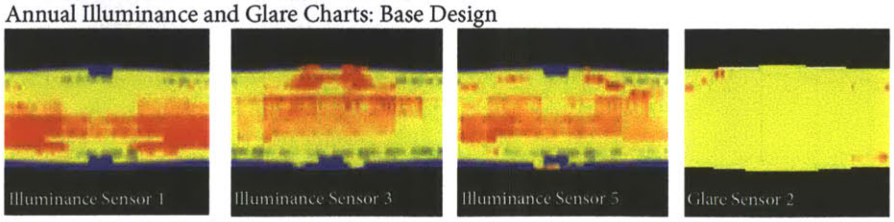


Figure 5: The sun charts for the pivoting shutters (first row) are compared to the sun charts for the base design (second row). The quantitative results are reiterated here: more yellow and blue represents a greater amount of light within-range and below-range; less red represents a smaller proportion of above-range illuminance levels.

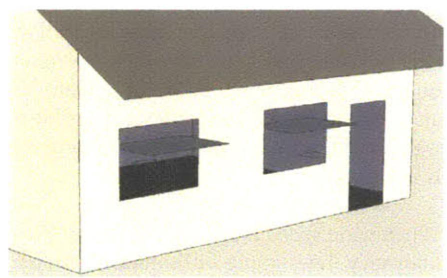


Figure 6: This alternative design has pivoting shutters while the base design is simulated with no shutters to represent open casement shutters.

SENSOR	DGP
GLARE 1	24%
GLARE 2	19%

Table 5: Glare levels in the pivoting shutter design

The lighting simulations show that the pivoting shutters have very little effect on glare levels (table 5). The open doorway is the most likely cause of high glare levels at sensor 1, which is the same in the base design.

#2 Pivoting Shutters

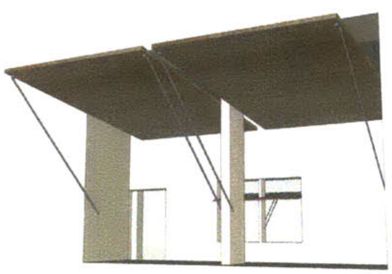
Case Study -Cambodia

As part of *Dlab: Schools*, a team of three Building Technology Masters students and one Architecture undergraduate student decided to address the problems with the current school shutter design. Current schools that had casement style shutters, similar to Sierra Leone's, were retrofitted with new shutters. These shutters were designed specifically to be adjusted according to weather conditions. Both awning and pivoting shutters were constructed and added to the classrooms. The price of each shutter was $38, including labor, which was significantly less costly than the wooden shutters, which are priced at $55 per shutter in Cambodia (prices differ from estimated prices in Sierra Leone).

Figure 8: Pivoting shutters in construction

Figure 9: Completed pivoting shutters in a Cambodian classroom.

Design Details



The major benefit of a pivoting design over the base design is user adjustability. Windows can be partially closed to block out directly sunlight while still allowing diffuse light into the classroom.

Benefits:
- The shutters provide overhead sun protection against direct sunlight
- User may adjust the shutters to a variety of angles
- The shutters can protect against rains while still allowing in light

Problems:
- Lighting simulations show more light in the classroom at below-range levels, because of the additional shading.
- The shutters do not protect against rain coming in at strong angles
- If shutters are too heavy, they could be difficult for young children to open

Ventilation

A stark contrast in the change of temperature is seen when the rear classroom windows are closed. This would be the case in the base design if there were heavy rains. Alternatively, the pivoting shutters could provide rain protection, allowing the windows to stay open and allow light and airflow in the building. When the rear windows are closed, there is no airflow when only wind-driven airflows are considered. For buoyancy flows, the difference in temperature between the base design when it was "rain protected"—for example with the pivoting windows—and the base design is 3.14 K. This significant change in temperature shows the benefit of having design alterations that allow the rear windows to stay open during rainy weather.

Model type	Airflow type	V (sm^3/s)	ACH	output ΔT (K)
Closed Rear Windows	wind-driven	0.0	0.0	n/a*
Pivoting Shutters	wind-driven	5.40	2.18	2.79
Closed Rear Windows	buoyancy-only	1.12	0.45	13.48
Pivoting Shutters	buoyancy-only	1.46	0.59	10.34
Closed Rear Windows	wind and buoy	1.12	0.45	13.48**
Pivoting Shutters	wind and buoy	4.45	1.79	3.40

*No wind-driven airflows are seen in the rainy-day wind-only model, therefore the output temperature cannot be calculated with the methods used in this report

**Because there are no wind-driven airflows in the rainy-day model, buoyancy flows stay constant when wind is added

Figure 10 shows CONTAM Visualization results for buoyancy-driven (left) and wind-driven (right) airflows. This reiterates the fact that windows on both sides of the classroom are very important, as wind-driven airflows are the most significant contributor to natural ventilation

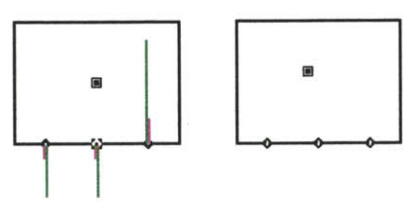
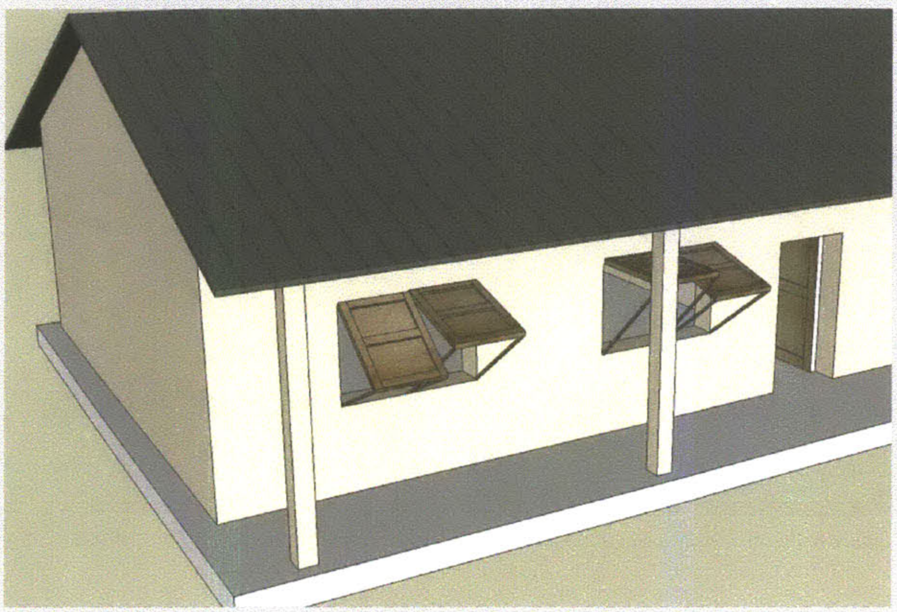


Figure 10: CONTAM Visualization

#4 Awning Shutters



Design Overview

Awning shutters can be made with wood, although a lightweight material such as metal or fiberglass would make operation easier. The awnings attach above the window and extend downward. While many awnings in commercial buildings are permanently attached at a fixed angle, many benefits are given with adjustability. For example, this design can close and lock (figure 13), securing the inside of the building as well as protecting from direct sunlight and rain.

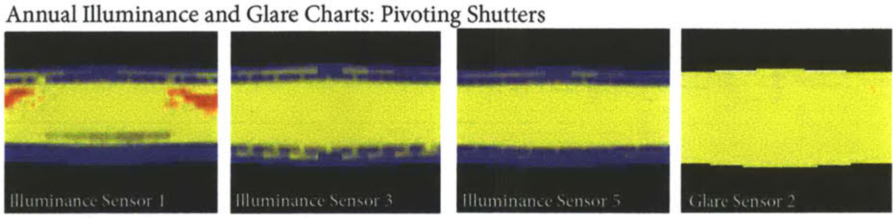
The awning shutters provide many of the same benefits that the pivoting shutters do. Unlike the pivoting shutters, the awning shutters may be added to windows constructed with rebar. However, if they are constructed with too heavy a material, they may be hard for small children to open.

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	72%	24%	4%
SENSOR 2	73%	22%	4%
SENSOR 3	83%	17%	0%
SENSOR 4	79%	21%	0%
SENSOR 5	78%	22%	0%
AVERAGE	**77%**	**19%**	**2%**

Table 7: A very similar percentage of in-range illuminance levels were found with the awning shutter design compared to the base design (77% vs. 76%). However, a much lower amount of above-range lighting was found in this design (2% vs. 15%).

Annual Illuminance and Glare Charts: Pivoting Shutters



Annual Illuminance and Glare Charts: Base Design

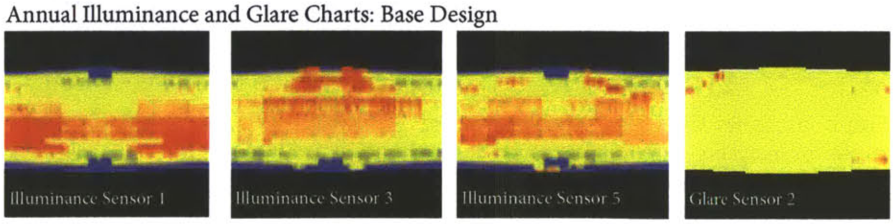


Figure 11: The sun charts for the awning shutters (first row) are compared to the sun charts for the base design (second row). Similar to the pivoting shutters, more yellow and blue represent a greater amount of light within-range and below-range; less red represents a smaller proportion of above-range illuminance levels.

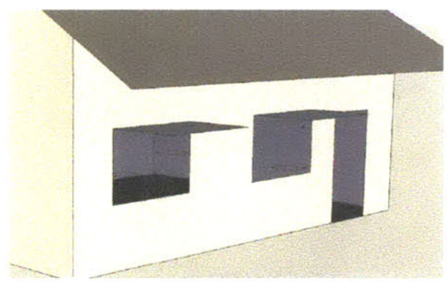


Figure 12. The awning shutter design uses planes above each window to represent the shutters. For simplicity, the awning shutters stay at 90º angle to the wall·

SENSOR	DGP
GLARE 1	25%
GLARE 2	17%

Table 8: Glare levels in the awning shutter design

While glare in the rear of the classroom was reduced, the glare in the front of the classroom unexpectedly increased (table 5).

#4 Awning Shutters

Case Study

In addition to installing pivoting shutters, as seen in the previous section, MIT *D-lab: Schools* constructed awning shutters. They were made of sheet metal riveted to a metal frame, to conserve the country's dwindling rain forest resources. A window prop was attached to the window frame with metal washers and bolts. The bolts were welded at increments along the window frame to allow the prop to fix the shutter angle.

Unlike the pivoting shutters, the awning shutters may be constructed wider than the window frame, adding more protection from rain coming in at angles. The example on the right extend 10 cm past the window frame on the ends.

Figure 13. Closed awning shutters

Figure 14. Open Awning shutters, adjusted at low angles

Thermal Comfort

In DesignBuilder, the interior temperature of the awning shutter design was lower than the base design by 0.9 K. Figure 15 shows how the thermal comfort of the awning shutters compares to other devices throughout the year.

In addition to comparing the awning shutters to the base design with open windows, these shutters were also compared to the base design with the casement shutters opened at 90º (figure 18). In the EnergyPlus simulations, the awning shutters design had a lower average temperature at the hottest periods of the year (October through March, figure 15) when compared to the open casement shutters ("sidefins").

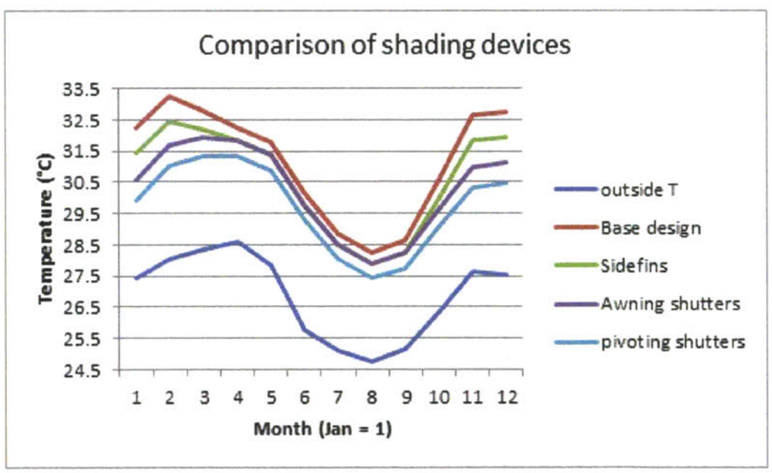


Figure 15: Graph representing interior temperature changes in different classroom designs over the course of one year.

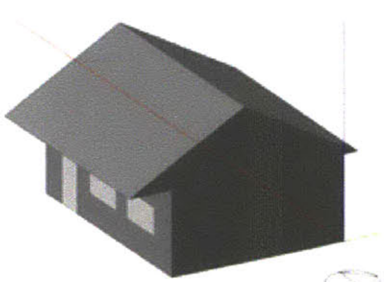


Figure 16: DesignBuilder base model

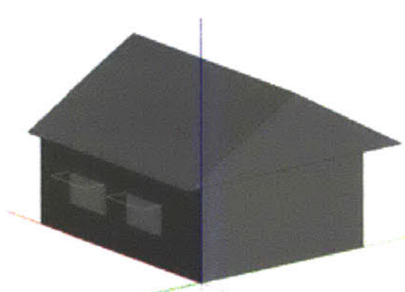


Figure 17: DesignBuilder awning model

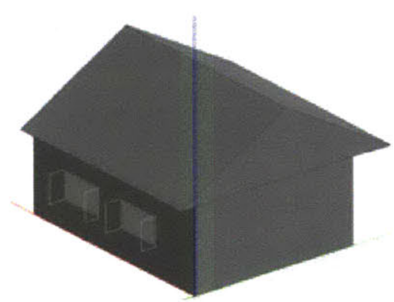
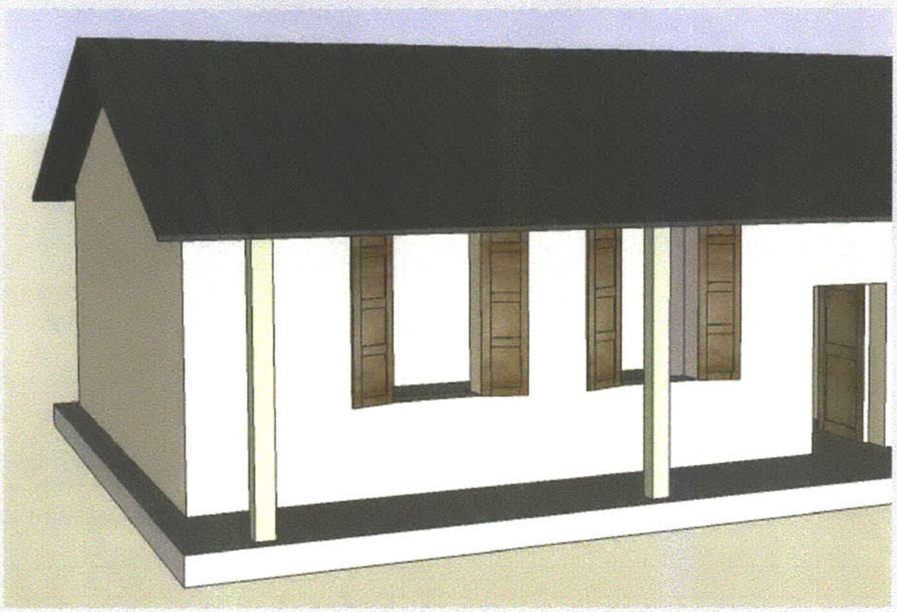


Figure 18: DesignBuilder base model with open shutters

#3 Elongated Windows



Design Overview

The elongated window design has the same open area and number of windows as the base design, but with a different shape. Therefore, it is not the size of the windows that is being compared, but the way the window is positioned.

Taller windows provide many benefits. First, this design reduces the need for a steel-reinforced concrete lintel above each window, which can reduce the overall costs. Second, taller windows allow light to penetrate deeper into the classroom. Last, because the windows do not have any glass panes in them, wind flow is affected by the height of the windows. Stack-effects from buoyancy-driven flows depend on the relative elevations of the window openings.

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	75%	14%	11%
SENSOR 2	69%	10%	20%
SENSOR 3	85%	12%	3%
SENSOR 4	84%	12%	4%
SENSOR 5	76%	13%	11%
AVERAGE	**78%**	**12%**	**10%**

Table 9: Slightly higher levels of light at within-range illuminance were seen in the long window design (78% vs. 76%). Overall, these levels are very positive compared to the base design because the amount of above-range illuminance was also decreased (10% vs. 15%), but the amount of below-range illuminance did not increase by much (12% vs 9%).

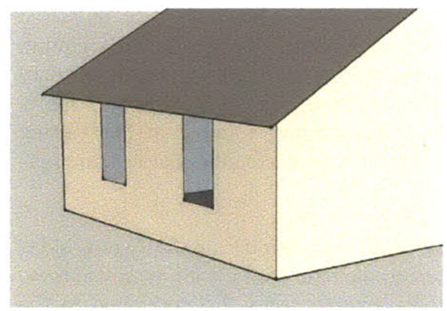
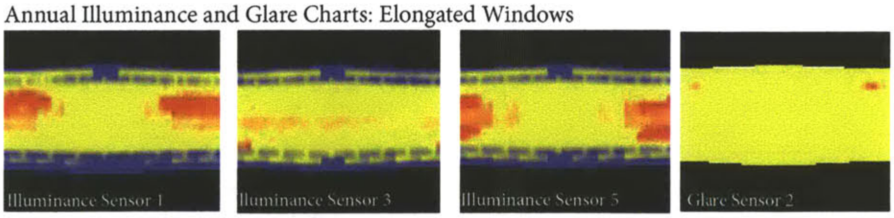


Figure 20: The alternative design lighting model has narrower, but taller, windows compared to the base design (rear view).

Annual Illuminance and Glare Charts: Elongated Windows



Annual Illuminance and Glare Charts: Base Design

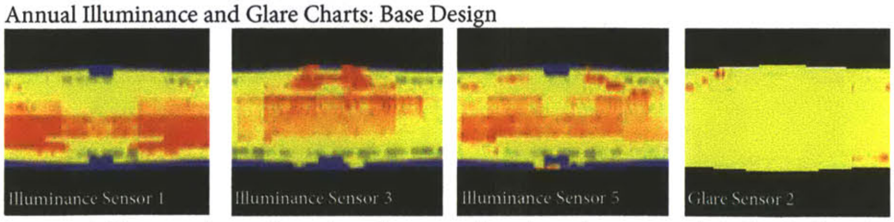


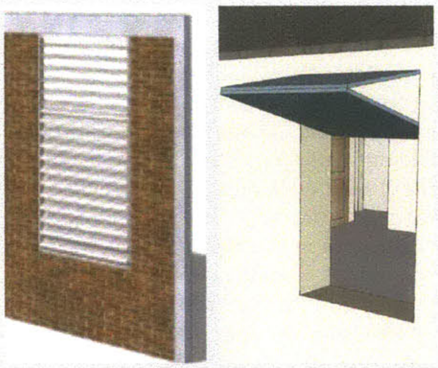
Figure 19: The sun charts show that all sensors have less above-range light levels than the base design, and that the glare levels have slightly lower amounts of above-range light levels.

SENSOR	DGP
GLARE 1	23%
GLARE 2	19%

Table 10: The glare levels decreased slightly overall by one percent DGP at each sensor.

#3 Elongated Windows

Design Details



Figures 22 & 23: A challenge with this new window shape is the shutter design because they would need to be customized. Alternatives to simple wooden shutters, such as slatted, or folding shutters could be used in the elongated window design.

Materials

Figure 21 shows the material differences in the elongated windows design compared to the base design. Steel and concrete costs are significantly reduced because steel-reinforced concrete lintels are not needed above the windows. However, steel is still used in the supporting columns and a concrete lintel is still needed above the doorway. Using construction data from 2010 from the non-profit VillageHope, approximately US$325 may be saved per classroom on elongated windows.

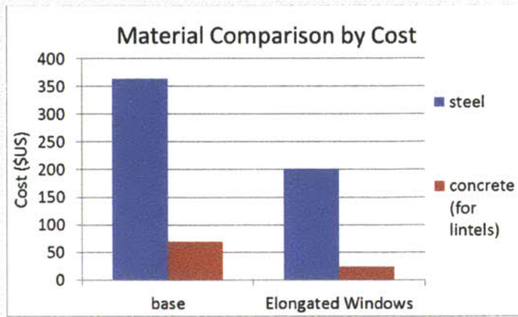


Figure 21: Material comparison by cost between the base design and the elongated windows

Ventilation

CONTAM results showed that buoyancy airflows increased when the windows were elongated (table 11). While wind-driven air flows stay constant because the total open area on each side of the classroom doesn't change, buoyancy-driven flows for the elongated windows increase when the wind speed is 0 m/s. When compared to the Base design. Buoyancy-only flows decreased the temperature 1.19 K from the base design.

Model	Air-flow type	V (sm^3/s)	ACH	output ΔT (K)
Base	buoyancy	1.46	0.59	10.34
Long windows	buoyancy	1.65	0.67	9.15
Base	wind & buoy	4.45	1.79	3.40
Long windows	wind & buoy	4.45	1.79	3.40*

*When wind speed is added to two-way buoyancy flows, the wind speed will cancel out some buoyancy flows going in the direction opposite of the wind.

Table 11: Material comparison by cost between the base design and the elongated windows

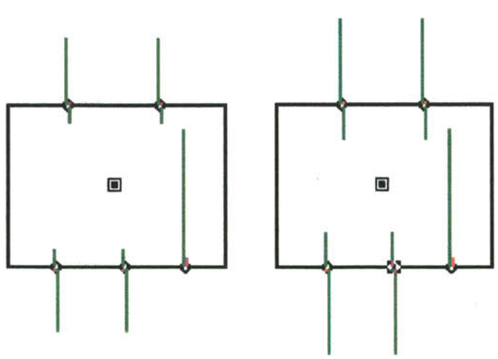


Figure 22: Buoyancy flows with a 0 m/s wind speed for the base design (left) and the elongated window desing (right).

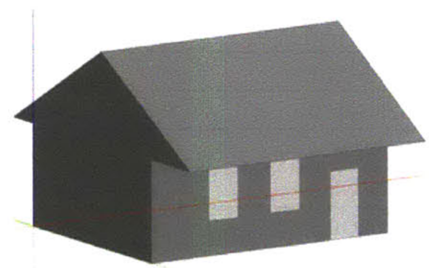


Figure 23: In EnergyPlus, the elongated window design resulted in a temperature decrease of 0.2 K.

	Average Temp (°C)
Long Windows	31.0
Base	31.2
Exterior	26.7

Table 12: Temperatures for the classroom interiors for the elongated window design and the base design, as well as the exterior-dry bulb temperature.

#5 Five Windows

Design Overview

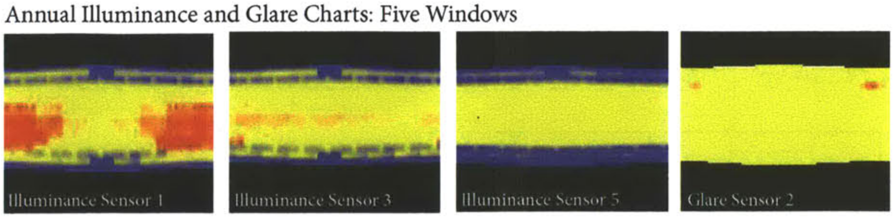
For maximum airflow, the orifice areas on both sides of the building should be equal. In the case of unequal openings, the smaller area, or the "bottleneck" will control the natural ventilation. The doorway, because it may be left open during hot periods of the day, gives the front of the building additional open area, despite an equal number of windows on each side. To offset this, the total area of the base-design windows were divided into five equal sized window openings, and three were placed at the rear side of the classroom to create a design with five windows. Therefore the open area on the rear side of the classroom is 3.8 m^2 and the front side is 4.2 m^2 (compared to 3.52 m^2 and 5.52 m^2 for the base design).

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	62%	5%	33%
SENSOR 2	59%	5%	36%
SENSOR 3	81%	10%	9%
SENSOR 4	82%	11%	7%
SENSOR 5	77%	12%	11%
AVERAGE	**72%**	**9%**	**19%**

Table 13: The five window design received 4% more light than the base design in the above-range levels. This 4% was subtracted from the in-range levels, leaving the five window design with 72% and the base design with 76%. These results show the importance of having shading protection in the rear of the classroom, as sensors 1 & 2 at the rear of the classroom are receiving high levels of above-range lighting.

Annual Illuminance and Glare Charts: Five Windows



Annual Illuminance and Glare Charts: Base Design

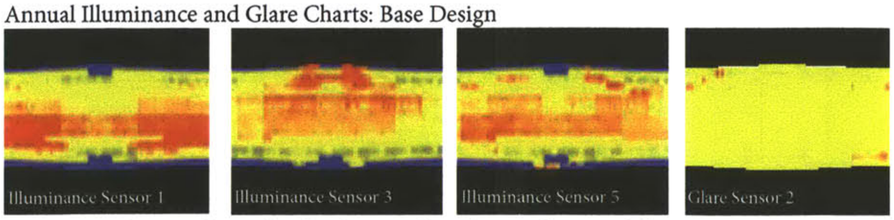


Figure 24: The sun charts for the five window design (first row) show a greater amount of above-range lighting (red), especially in sensor 1, the sensor placed at the rear side of the classroom.

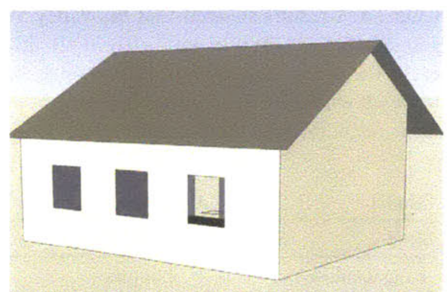


Figure 25: The model above shows three windows on the rear side of the classroom. These three windows have a total open area of 4.2 m^2 compared to the base designs rear open area of 3.52 m^2

SENSOR	DGP
GLARE 1	24%
GLARE 2	19%

Table 14: Slightly lower glare levels are seen in the rear of the classroom in the five window design.

Design Details

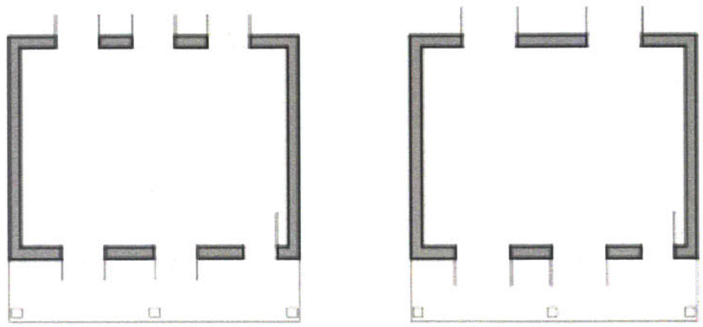


Figure 26: The floor plans of the five window and the base design. Both models have equal total open area, but the 5 window model has one additional window in the rear.

Design Details

Air Flow

Table 15: In both CONTAM and EnergyPlus, the five window design increases airflow through the classroom and reduces interior temperatures. Buoyancy flows with no wind speed do not affect the temperature change, but the wind-driven flows increase as the window area on each side of the classroom become closer to equal.

Model	Air-flow type	V (sm^3/s)	ACH	output ΔT (K)
Base	wind-driven	5.40	0.59	2.79
Five windows	wind-driven	5.82	0.67	2.59
Base	wind & buoy*	4.45	1.79	3.40
Five windows	wind & buoy	4.45	1.92	3.17

*buoyancy flows with no wind speed do not change from the base design

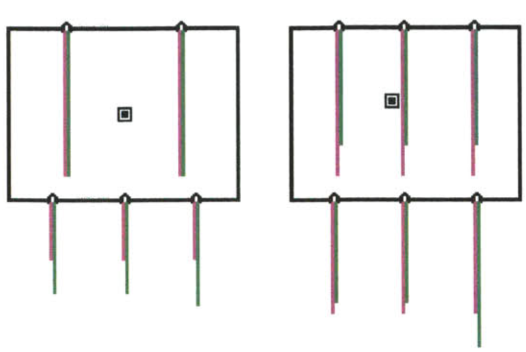


Figure 27: The base design compared to the five window model in CONTAM for wind-driven airflows

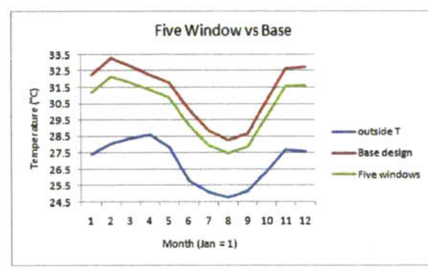


Figure 28: In EnergyPlus, the temperature of the five window design decreased by 1 K, having an average interior temperature of 30.2 °C vs 31.2 °C.

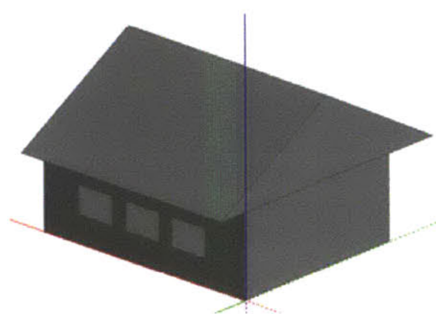
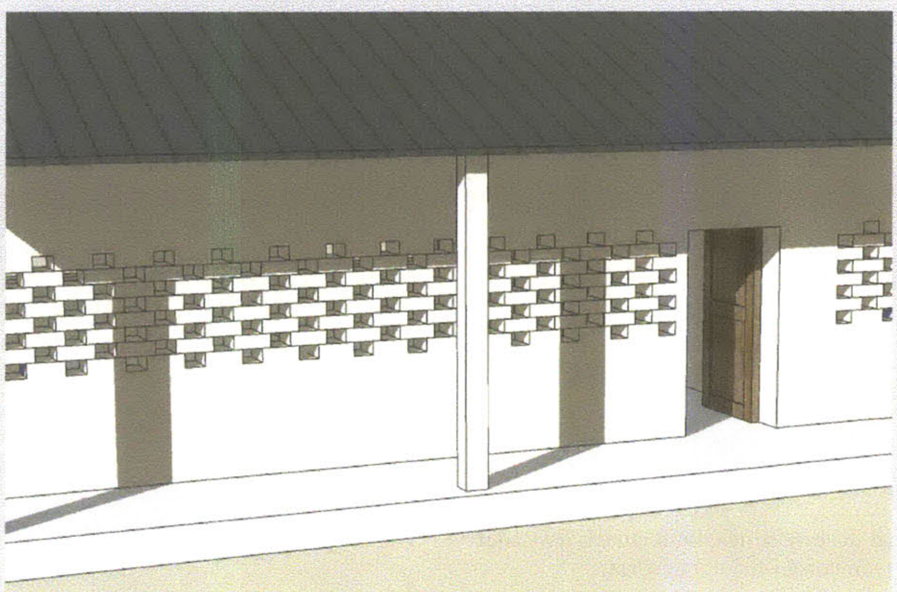


Figure 29: DesignBuilder model for the five window design that was used to run EnergyPlus simulations.

#6 Jali Walls



Design Overview

"Screen" or "jali" windows are an alternative type of window that is common is Sierra Leone. While the traditional type of jali wall consists of bricks placed with gaps in between them, the screen walls in Sierra Leone are made with decorative concrete blocks. This type of window diffuses glare and creates interesting light patterns inside the classroom. Like the elongated windows, these windows do not need supporting lintels above them, since the bricks give additional support. A material comparison with cost estimates is shown in figure 35.

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	62%	6%	32%
SENSOR 2	62%	6%	32%
SENSOR 3	71%	6%	22%
SENSOR 4	77%	9%	14%
SENSOR 5	76%	10%	14%
AVERAGE	**70%**	**7%**	**23%**

Table 16: The lighting simulations showed that the jali wall design has less light at in-range levels and more light above-range. However, the model used for lighting was simplified, and real-work examples would have smaller openings and greater wall-thickness, which would have a large impact on results.

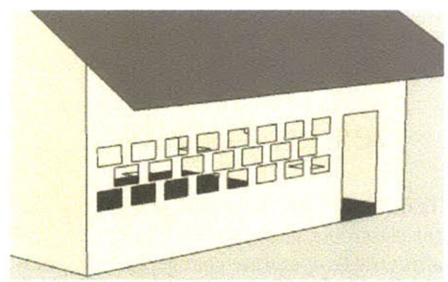
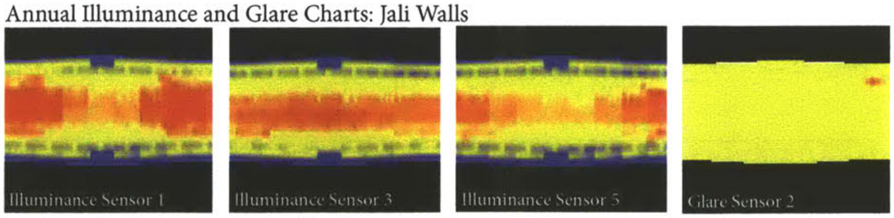


Figure 31: The jali walls lighting model was simplified, ignoring wall thickness and using larger openings than real-life examples. The total open area for each model is the same, however.

Annual Illuminance and Glare Charts: Jali Walls



Annual Illuminance and Glare Charts: Base Design

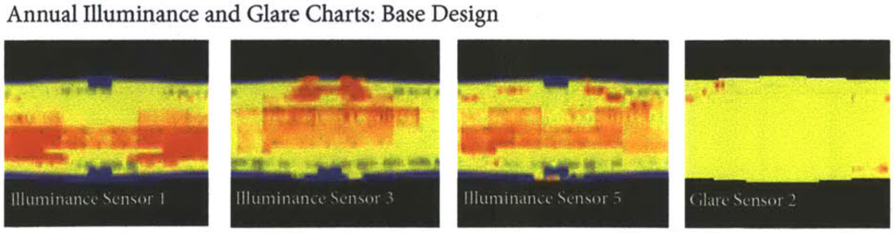


Figure 30: The sun charts for the jali walls have much more red in all sensors—showing the increased light at the above-range illuminance levels.

SENSOR	DGP
GLARE 1	24%
GLARE 2	19%

Table 17: The amount of glare in the jali walls is slightly reduced from 20% to 19% in glare sensor 2.

#6 Jali Walls

Materials

Case Study

In Sierra Leone, screen windows made out of decorative concrete blocks are common. A survey of teachers showed that they were very satisfied with these types of windows. In addition to diffusing the light, the thickness of the walls prevent rain from entering.

Figure 32: Sierra Leone Church primary school in Lunsar, Sierra Leone.

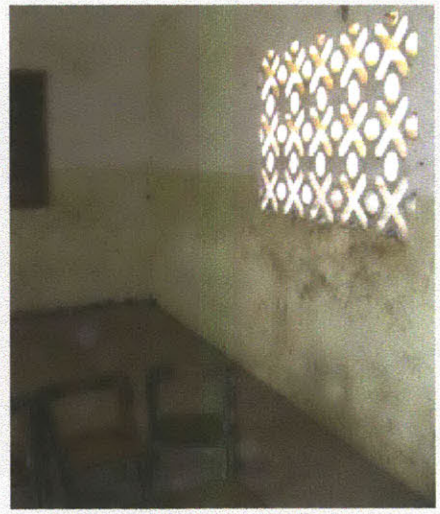


Figure 33: The District Council primary school in Lunsar, Sierra Leone.

Design Details

Jali walls give security in the building without having to put rebar or locked shutters on the windows. Compared to regular walls, they allow light and airflow into the space. Many architects like Jali walls for their interesting light patterns they can produce (figures). However, while reducing glare is good, these patterns may be distracting in a classroom.

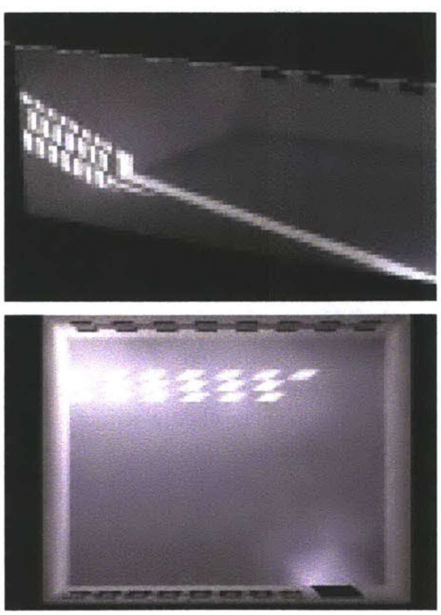


Figure 34: Renderings of Jali Wall patterns produced during lighting simulations using LightSolve.

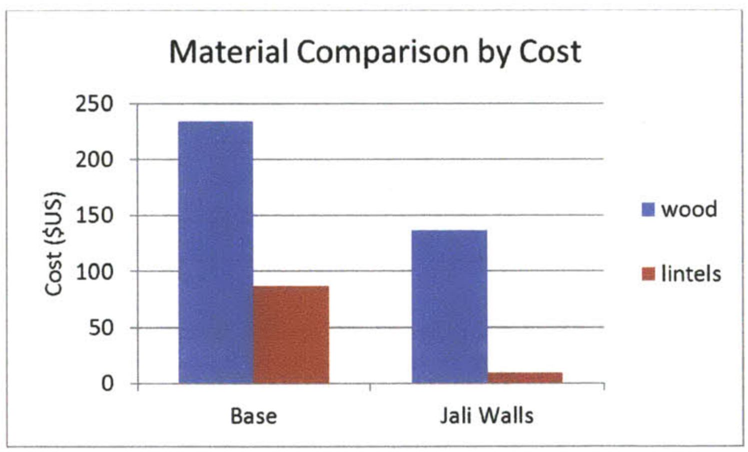
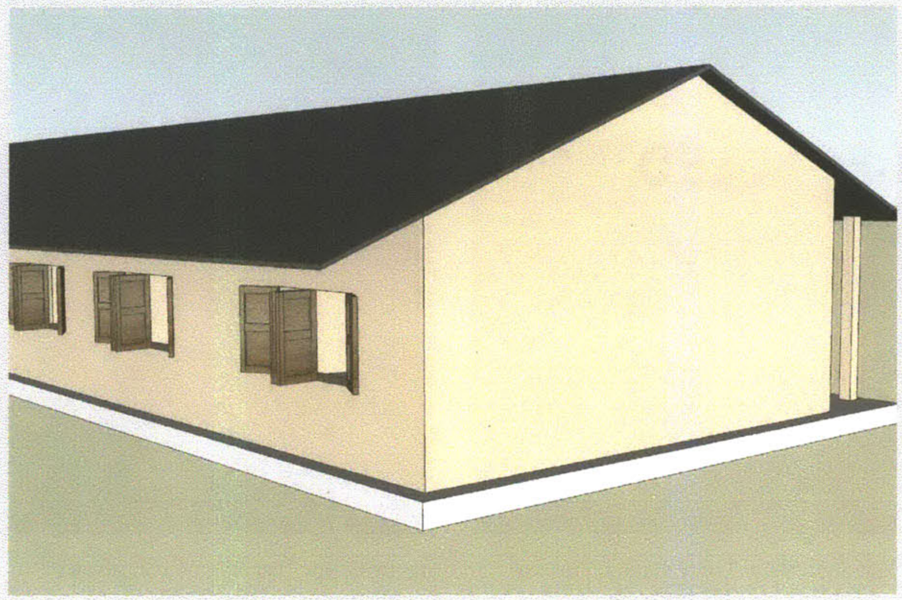


Figure 35: Like the elongated windows, the jali wall design does not need lintels above the windows, if constructed correctly. Therefore, the amount of concrete and steel reinforcing rebar is reduced.

#7 Extended Rear Overhang



Design Overview

The rear of most classrooms in Sierra Leone has a very short roof overhang. While the front of the building is shaded from rain and direct sunlight because of the large porch, the rear of the building has almost no protection from the elements. Therefore, a long roof overhang provides some of the same benefits as window protections, such as the awning shutter design.

For example, when it is raining, the rear windows often have to be closed, and therefore very little light can enter the classroom. With a longer overhang, this problem can be avoided for most rains. For many classrooms, the rear is used as an access way. With a long roof overhang, this design can provide a shaded social space as well.

Daylighting

	AT	BELOW	ABOVE
SENSOR 1	74%	20%	7%
SENSOR 2	77%	16%	7%
SENSOR 3	85%	15%	0%
SENSOR 4	86%	14%	0%
SENSOR 5	84%	15%	1%
AVERAGE	**81%**	**16%**	**3%**

Table 19: The extended rear overhang gave the same average lighting results as the pivoting shutters, yet had higher in-range levels of light at sensor 5, located in the center of the classroom (84% vs 81%).

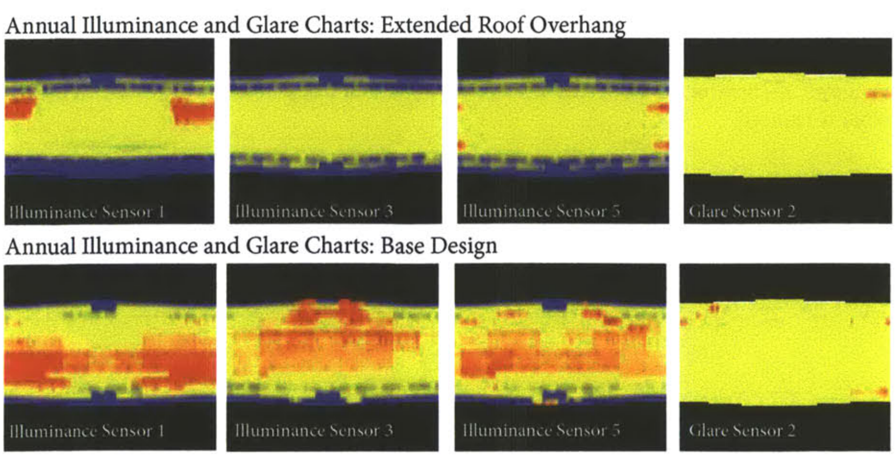


Figure 36:The sun charts above show that the extended rear overhang has very little light in the above-range values (red), with a significant portion of its light levels at-range (yellow).

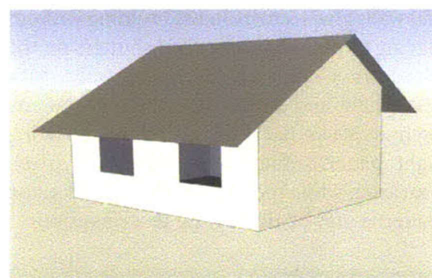


Figure 37: The extended overhang in the rear of the classroom is 1 m longer than the base design. With the altered design, a 1.5 m long roof overhang is shading both the front of the classroom and the rear of the classroom.

SENSOR	DGP
GLARE 1	24%
GLARE 2	18%

Table 20: The amount of glare in the extended roof overhang is slightly reduced from 20% to 18% in glare sensor 2.

#7 Extended Rear Overhang

Case Study

One example of extended roof overhangs is seen in a school constructed by the non-profit group BETT (Basic Education and Teacher Training), who have built schools in Southeast Asia with improved features based on user evaluations. These schools use a 1.9 m roof overhang on both the rear and front sides of the classroom (figure 38).

This contrasts with a typical classroom overhang of about 0.5 m in the rear (figure 37). In the school on the right, the shaded space created in the back of the classroom allows for an additional walkway that children use to go to the latrines, located behind the classrooms.

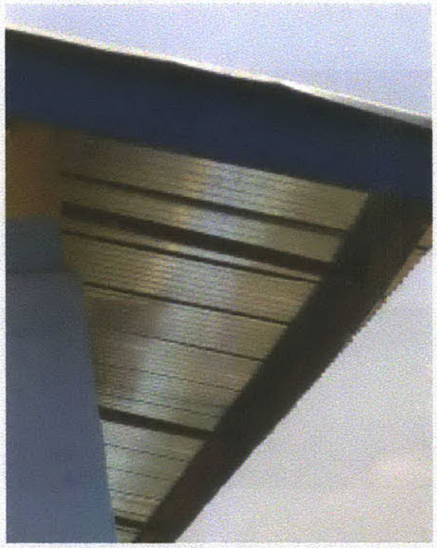


Figure 38: School design in Sierra Leone with a short overhang (approximately 0.5m)

Figure 39: BETT School with a 1.9m overhang in the front and rear of the classroom.

Thermal Comfort

In DesignBuilder, the interior temperature of the extended roof overhang design was lower than the base design by 1.2 K. This was 3.1 K higher than the exterior dry bulb temperature. Figure 40 shows how the thermal comfort of the extended rear overhang compares to other designs throughout the year.

In addition to comparing the extended roof to the base design, the total effects of having a roof at all were also simulated. This effect is due to both the additional material insulation that the roof provides as well as the shading from the roof overhang. The base design without a roof increased the temperature 1.4 K above the base design and 2. 6 K above the extended rear overhang design.

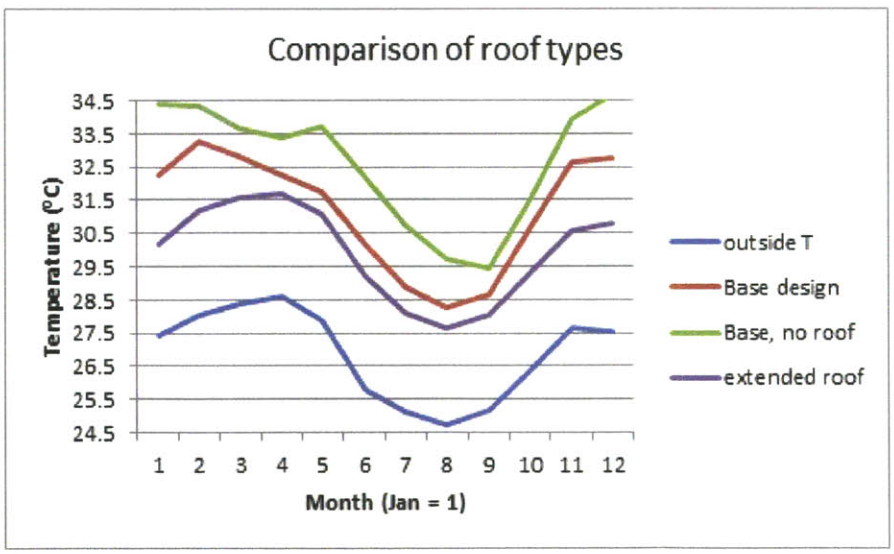


Figure 40: Graph representing interior temperature changes over the year of different classroom roof designs.

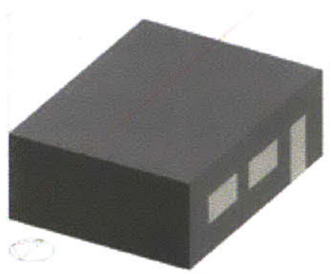


Figure 41: DesignBuilder model with no roof

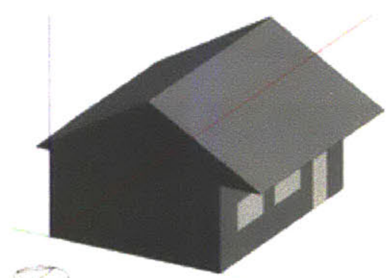


Figure 42: DesignBuilder base model

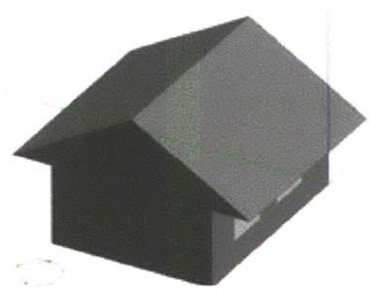
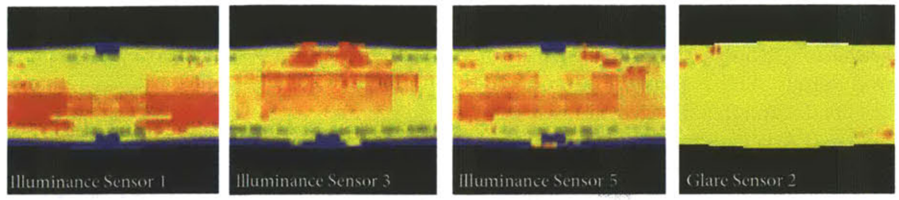


Figure 43: DesignBuilder extended rear overhang design

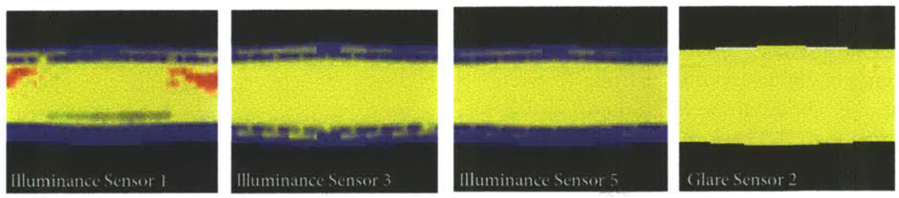
Summary & Next Steps

LightSolve: Sun Charts

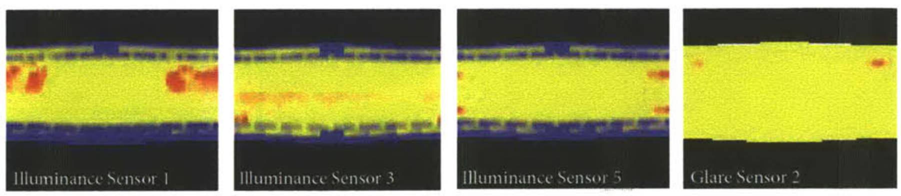
Base



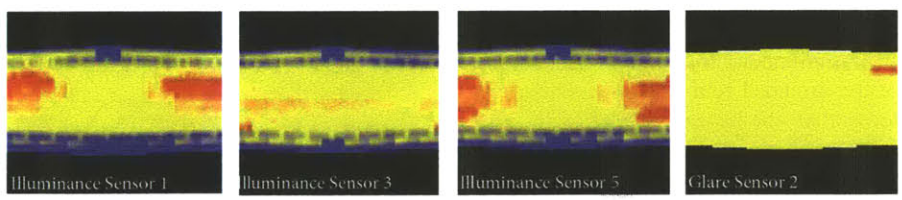
Awning Shutters



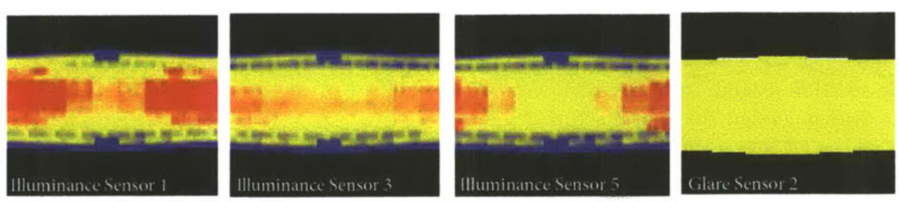
Pivoting Shutters



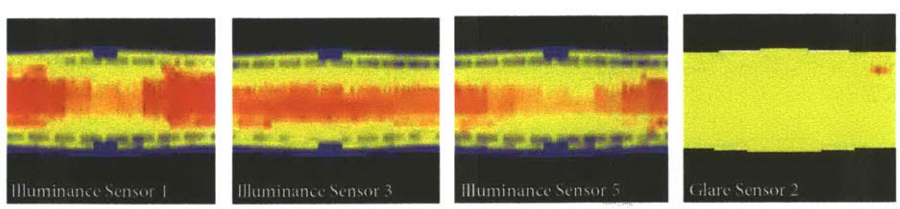
Elongated Windows



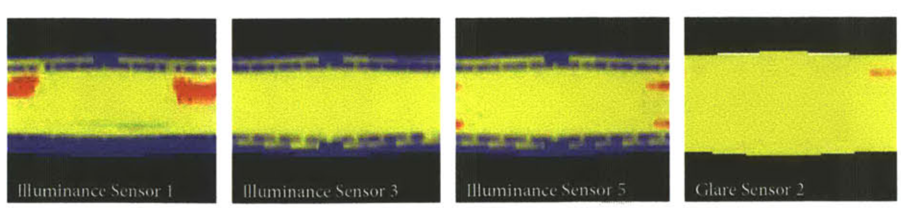
Jali Walls



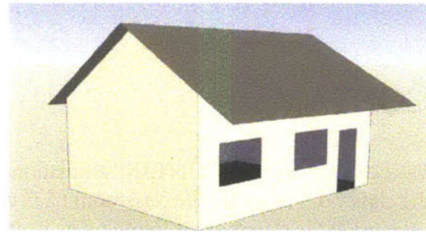
5 Windows

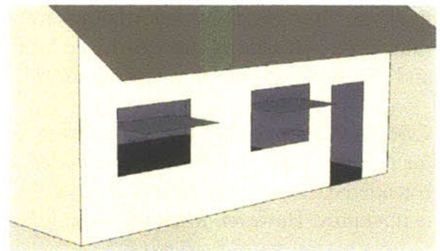


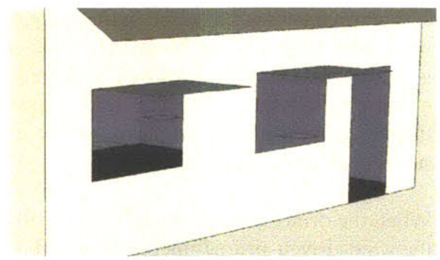
Extended Roof

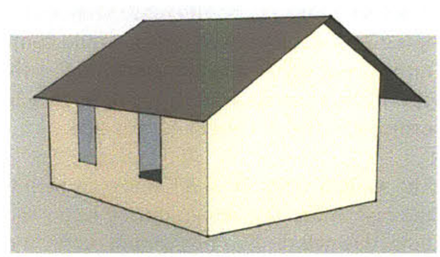


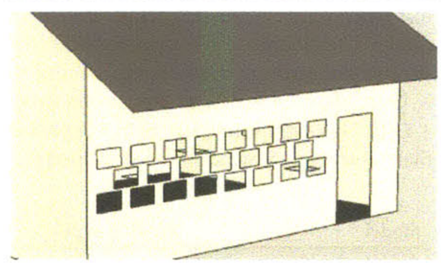
Summary

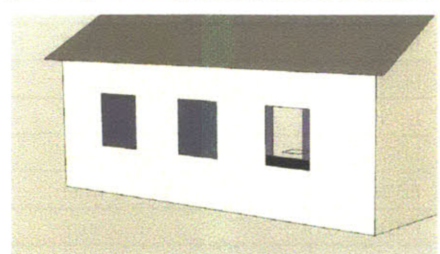


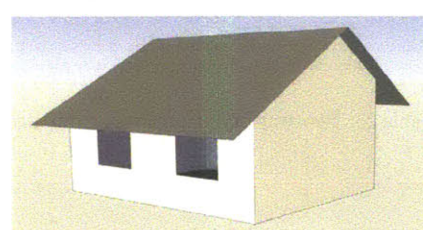












LightSolve

The results of the lighting simulations showed that some of the designs that were meant to shade the building--the awning shutters, the pivoting shutters, and the extended roof--succeeded in reducing illuminance levels that were above optimal (>800 lux). Unfortunately, these designs also resulted in a greater percentage of light below-range (<300 lux). With these designs, there is a trade-off between a greater percentage of below-range light levels and a greater percentage of in-range levels. However, the benefit of rain protection that these designs give may offset this. All together, the pivoting shutters and the extended roof give the best lighting results of the three shading designs (table 21).

Benefits:

- High levels of light at optimal range (300-800 lux)
- Very little light with above-range illuminance levels (>800 lux)
- Provide rain protection

Problems:

- Greater amount of light at levels below optimal range (<300 lux)

	AT	BELOW	ABOVE
BASE	76%	9%	15%
AWNING	77%	21%	2%
PIVOT	81%	16%	3%
EXTENDED ROOF	81%	16%	3%

Table 21: The shading designs (awning and pivoting shutters as well as the extended roof overhang) increase both in-range illuminance levels and below-range levels.

The elongated window design also provides additional shading because a higher proportion of the open area is protected by the roof. Light levels improved overall, reducing the above-range illuminance levels and increasing the in-range illuminance levels (table 22). Unfortunately, this design still does not provide full rain protection that the other designs give. This design does reduce material use though, and further research on the lighting conditions throughout the room should be conducted to ensure that narrower windows do not leave "dark spots" in areas of the classroom that are not tested.

	AT	BELOW	ABOVE
BASE	76%	9%	15%
LONG	78%	12%	10%

Table 22: Lighting conditions of the elongated window design compared to the base design

Finally, the five window design and the jali wall design need further research before drawing any conclusions. For example, the five window design has more open area at the rear of the classroom, but does not provide additional shading. Therefore, light levels above-range increased substantially from the base design (23% vs. 15%).

Additionally, the jali wall model was greatly simplified to expedite simulation time. The model has no wall thickness and does not accurately depict the size of each opening. Therefore, with greater complexity and more research, greater accuracy can be achieved in the lighting simulation before drawing conclusions about the lighting quality of this design.

	AT	BELOW	ABOVE
BASE	76%	9%	15%
JALI	70%	7%	23%
5 WINDOW	72%	9%	19%

Table 23: Lighting conditions of the elongated window design compared to he base design

Summary

CONTAM

The design goal in the CONTAM simulations is to get the change in temperature from outside the classroom to inside the classroom (ΔT) as close to zero as possible. The interior temperature inside the classroom is found using heat gain calculations and CONTAM outputs for airflow rate. The base, elongated windows, five windows, and the designs that give the classroom rain protection were all simulated. The "orifice area" airflow model measures wind-only flows and the "two-way buoyancy" model measures buoyancy flows with and without wind.

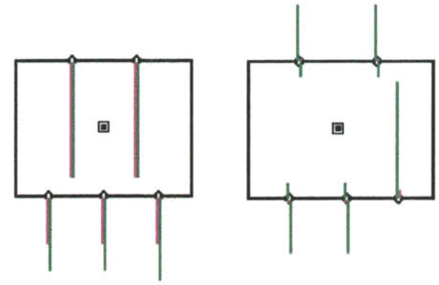


Figure 44: CONTAM visualization with wind-driven flows and for buoyancy-driven flows in the base design.

CONTAM showed that the wind-driven airflows within the classroom are very important for natural ventilation. If the wind-speed is 0 m/s, and therefore only buoyancy flows are considered, the interior temperature of the base design is 10.34 K higher than the outdoor temperature. However, when wind was added to the buoyancy flows, ΔT was only 3.40 K.

The buoyancy flows increased in the elongated window design, decreasing the ΔT with 0 m/s wind from 10.34 K (base design) to 9.15 K. At such high temperatures, any increase in airflow is important. However, because the alteration is small, this difference is small. If the height of the windows were increased more, a greater change would be seen. Additionally, because the elongated windows are narrower, the number of windows could be increased, having a substantial effect of overall airflow.

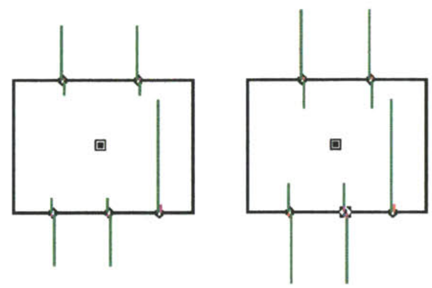


Figure 45: Buoyancy flows with a 0 m/s wind speed for the base design (left) and the elongated window design (right).

When the orifice area on the rear side of the classroom nears a value equal to the front side, the wind-driven airflows increase, as in the case of the five window design. For wind-driven flows, the temperature difference between the base design model and the five windows model was 0.2 K. An improved design would combine these two effects, making the front and rear orifice areas equal, and elongating each window as well. The temperature differences would also increase as the scale of the difference increases—such as longer windows or equivalent orifice areas on the front and rear side.

The starkest contrast in ΔT was seen with the rear classroom windows closed, as would be the case in the base design during heavy rains. When the rear windows are closed, two-way flows through the building cannot occur, and the natural ventilation with any wind speed is 0 m/s when only considering wind-driven airflows. Therefore, only buoyancy flows affect this model. The difference in temperature between the base design when a rain protected design—such as the pivoting shutters, the awning shutters, and the extended rear overhang—is 3.14 K. The difference between a rain protected design and the long window design during rains is 4.33 K. This significant change in temperature shows the benefit of having design alterations that allow the rear windows to stay open during rainy weather.

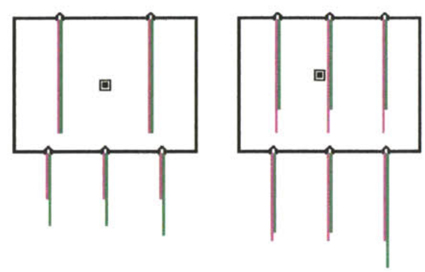


Figure 46: The base design compared to the five window model in CONTAM for wind-driven airflows

Model	Air-flow type	V (sm^3/s)	ACH	output ΔT (K)
BASE	Buoyancy	1.46	0.59	10.34
BASE	Buoy & wind	4.45	1.79	3.40
LONG	Buoyancy	1.65	0.67	9.15
LONG	Buoy & wind	3.41	1.78	3.41
FIVE	Buoyancy	1.46	0.59	10.34
FIVE	Buoy & wind	4.77	1.92	3.17
RAIN PROTECTED*	Buoyancy	1.12	0.45	13.48
RAIN PROTECTED*	Buoy & wind	1.12	0.45	13.48**

*Rain protected design may include the pivoting shutters, awning shutters, or extended rear overhang.
**Because there are no wind-driven airflows in the rainy-day model, buoyancy flows stay constant when wind is added.

Table 23: Two-way buoyancy flows simulated in CONTAM

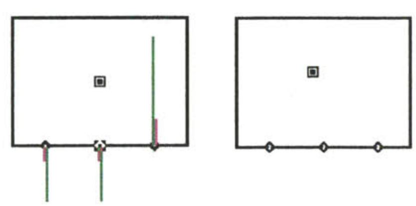


Figure 47: CONTAM Visualization for the base design during rains. Buoyancy flows are represented on the left while wind-driven flows (none) are on the right.

DesignBuilder/EnergyPlus

DesignBuilder (2010) in combination with EnergyPlus (2009) was used to simulate the overall thermal comfort of the building. Like CONTAM, the difference in temperature from outside the building to inside the building (ΔT) was focused on. Unlike the CONTAM results, EnergyPlus calculates the solar heat gain within the program. In the classroom simulations, all mechanical cooling, air conditioning, equipment, and lighting systems are turned off. The airflow that is modeled depends on climate data—such as average temperatures and wind speeds—from the region as well as the simulation inputs and the building geometry.

The effect of the additional 1 m overhang on the rear side of the classroom in the elongated roof overhang was first analyzed. To simulate the total effect of material insulation as well as shading of the roof, the elongated roof design was compared to both the base design and the classroom design with no roof at all (figures 48-50). The total temperature difference from outside the classroom to inside the classroom was 3.1 K in the elongated window design (table 25), a 1.2 K decrease from the base design and a 2.6 K from the classroom with no roof at all.

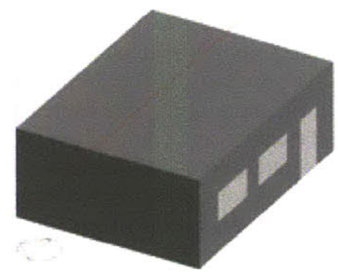


Figure 48: DesignBuilder base model

Model	Average Temperature (°C)	output ΔT (K)
BASE	31.2	4.3
BASE, NO ROOF	32.6	5.7
EXTENDED OVERHANG*	29.9	3.1

*The roof overhang is extended by 1 m in the rear of the classroom

Table 25: Difference in temperature from outside to inside the classroom in models with different roof types

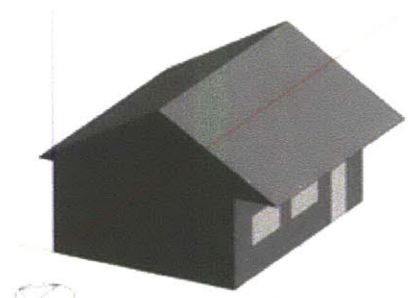


Figure 49: DesignBuilder awning model

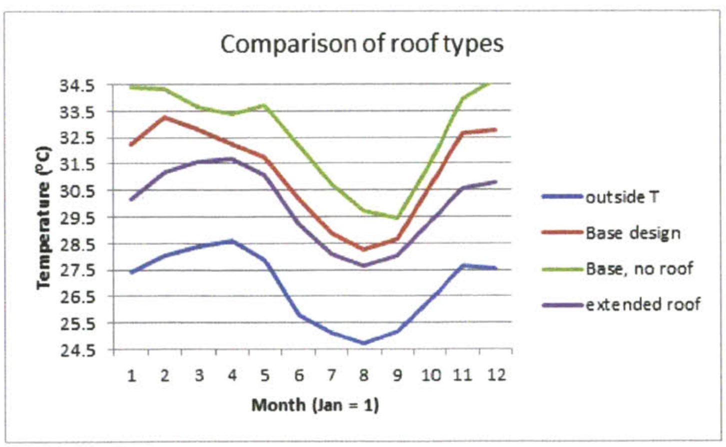


Figure 51: Comparison of roof types in DesignBuilder/EnergyPlus

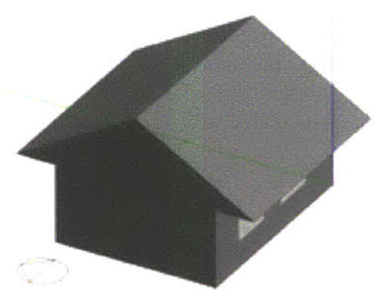


Figure 50: DesignBuilder base model with open shutters

(DesignBuilder/EnergyPlus summary continued on next page)

Summary

DesignBuilder/EnergyPlus Continued

Window shading devices--the pivoting shutters, the awning windows, and horizontal sidefins that could be opened on the base design--were also compared in DesignBuilder/EnergyPlus. The pivoting shutters were modeled as a combination of interior and exterior shading, with a 0.66m extending outside the classroom at a 60° angle and 0.33 m protruding inside the classroom at the same angle. This slanted angle had a significant impact on blocking heat gains inside the classroom compared to the other shading devices. The pivoting shutters and the awning shutters both improved thermal comfort inside the classroom. The awning shutters decreased interior temperatures during the hottest times of the year and the pivoting shutters decreased temperatures throughout the year (figure 52).

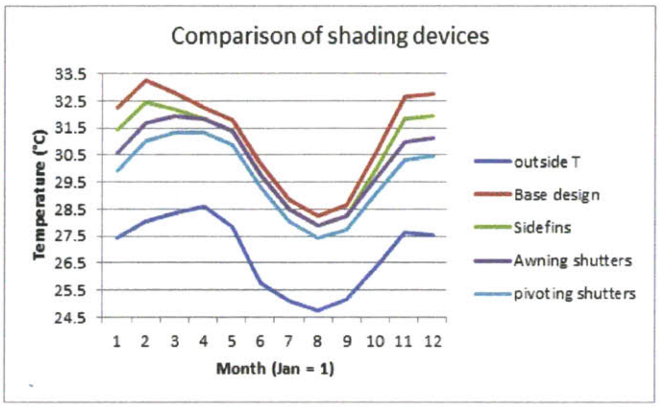


Figure 52: Comparison of shading types in DesignBuilder/EnergyPlus

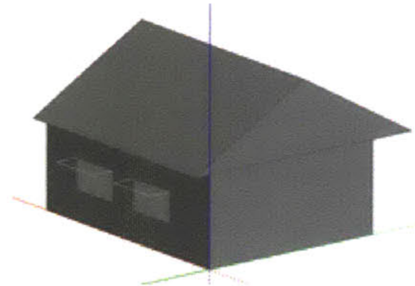


Figure 53: DesignBuilder awning model

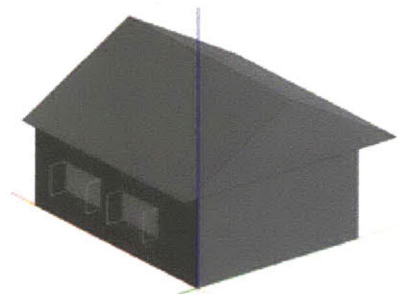


Figure 54: DesignBuilder sidefins model

Last, the five window design and the long window design were simulated. Compared to the base design, the interior temperature of the five window design was 1 K lower and the long window design was 0.1 K lower. As with the CONTAM results, this difference is small, but could be increased with a larger-scale change.

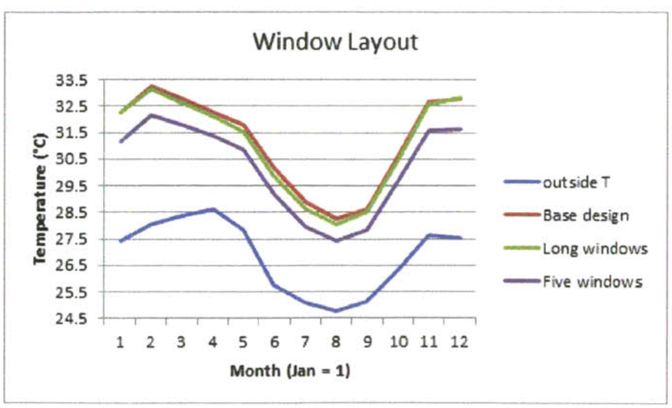


Figure 57: Comparison of window layouts in DesignBuilder/EnergyPlus

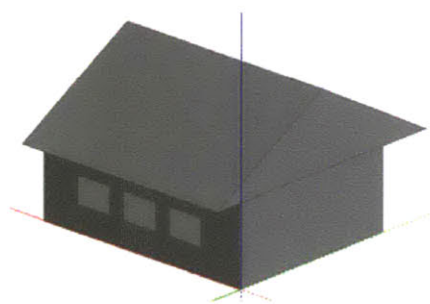


Figure 55: DesignBuilder five windows model

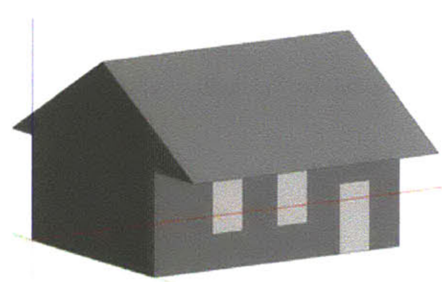


Figure 56: DesignBuilder long windows model

Discussion/Next Steps

The research conducted in this report is just the beginning. The LightSolve results showed that having additional shading on the rear windows will not compromise the overall lighting quality and will reduce the light levels that are too high. However, there are many inconclusive results in the lighting analysis that need further study. For example, the lighting was tested at five sensor planes within the classroom. For a few of the designs, such as the long windows, jali walls, and five windows, the results were lacking in knowledge of the lighting throughout the entire classroom. Therefore, more illuminance sensor planes are needed to fully grasp the lighting quality.

This problem was found with the glare sensors as well. Because the door to the classroom is left wide-open, sensor 1, located at the front of the classroom, had very high levels of glare. To understand the differences in lighting quality between each design, glare needs to be assessed at more locations within the classroom. A third shortfall in the lighting simulations was the complexity of the model. The jali wall results were inconclusive because the model was overly simplified and did not accurately depict the wall thickness or size of the openings that would have a large effect on lighting quality.

In the airflow models, the small scale of each change resulted in small scale temperature changes. For more dramatic changes, the changes must be made at a larger scale. Additionally, a scheduled airflow model was used in EnergyPlus that simplified the natural ventilation and may not have fully represented the wind-driven and buoyancy flows. More research is needed to ensure that the full effects of airflow are simulated.

Despite these shortfalls in the simulations, small changes in classroom design can be beneficial to the building performance and they can reduce costs. The next steps of this research is to simulate combinations of these designs and to increase the breadth of alternatives. For example, a wider breadth of designs may include roof insulation to reduce solar heat gain. Additionally, combining the five window design and an extended roof overhang may increase optimal light levels at the rear of the classroom as well as increasing air flow.

Chapter 7

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Chapter 8

Appendix

Appendix I

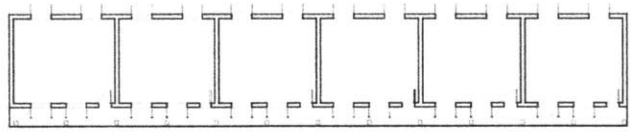
1.1 Table 1: Mean monthly temperatures, wind speed, precipitation days, and rainfall[iii]

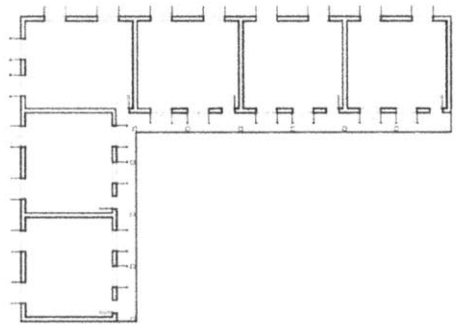
	Mean Temp	Mean Min Temp	Mean Max	Mean Prec. (mm)	Mean Prec. Days	Mean Wind	Relative Humidity
Jan	26.5	23	30	8	1	1	73
Feb	27	23	31	6	1	1	72
Mar	28	24	31	28	2	1	72
Apr	28	25	31	68	5	1	79
May	26	25	31	214	13	1	81
Jun	26	23	29	522	20	1	85
Jul	26	23	28	1190	25	1	88
Aug	25	23	27	1078	24	1	86
Sep	26	23	28	800	23	1	89
Oct	26	22	29	333	19	1	84
Nov	27	23	30	148	11	1	82
Dec	26.5	23	30	38	5	1	78

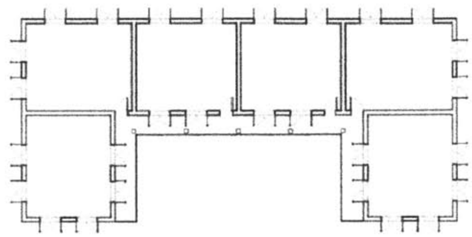
1.2 Comparing number of classrooms, dimensions of each room, and the building layout

No	Name	Number of classrooms	Dimension of each room (m)	Shape
1.	RC Primary Catholic School, Kamasondo	6	5.5 x 6.1	linear
2.	Romance Junior Secondary School, Kamasondo	6	6.0 x 8.2	U-shaped
3.	Primary school West of Kamasondo	4	5.8 x 8.6	linear
4.	RC Rosint School	4	5.8 x 8.3	linear
5.	Primary School south of Rokholifa	4	7.1 x 9.1	linear
6.	Ahmadiyya Muslim Primary School, Lunsar	6	6.2 x 8.8	L-shaped
7.	Holy Cross Catholic Primary School, Lunsar	6	6.7 x 8.0	linear
8.	Marampa Islamic School, Lunsar	6	5.5 x 6.5	linear
9.	District Council School (Government School), Lunsar	6	6.0 x 7.9	L-shaped
10.	R.C. Primary Adele Pavariani, Lunsar	6	6.1 x 7.9	L-shaped
11.	Sierra Leone Church Primary School, Lunsar	6	6.2 x 8.7	linear
12.	Moslim Brotherhood Primary and Secondary School, Lunsar	9	6.8 x 9.4	linear
13.	Catholic Mission Primary School, Lunsar	6	6.5 x 7.1	linear
	Standard/Average	Standard: 6	6.2 x 8.0	linear

1.3 Simplified Layout Types: Linear, U-shaped, and L-shaped







1.4 Comparing Window Characteristics

No.	Name	Window size (m)	No. of windows	% open area in windows	Open area (m^2)
1.	RC Primary Catholic School, Kamasondo	1.2 x 0.9	3	100%	5.3
2.	Romance Junior Secondary School, Kamasondo	2.0 x 1.2	5	50%	8
3.	Primary school West of Kamasondo	2.0 x 1.2	3	50%	5.6
4.	RC Rosint School	1.4 x 1.4	3	100%	7.9
5.	Primary School south of Rokholifa	2.0 x 1.2	3	100%	9.2
6.	Ahmadiyya Muslim Primary School, Lunsar	1.4 x 1.1	4	50%	5.1
7.	Holy Cross Catholic Primary School, Lunsar	1.1 x 1.1	5	100%	8.1
8.	Marampa Islamic School, Lunsar	1.1 x 1.0	4	100%	6.4
9.	District Council School (Government School), Lunsar	1.2 x 0.9	3	50%	3.6
10.	R.C. Primary Adele Pavariani, Lunsar	1.4 x 1.1	5	100%	9.8
11.	Sierra Leone Church Primary School, Lunsar	1.8 x 1.1	5	50%	7.0
12.	Moslim Brotherhood Primary and Secondary School, Lunsar	2.4 x 1.2	5	50%	9.2
13.	Catholic Mission Primary School, Lunsar	1.4 x 1.1	5	100%	9.7
	Standard/Average	1.6 x 1.1	4.1	Standard: 100%	7.3

1.5 Detailed lighting data

No.	Name	Open area (m^2)	Illuminance min/max	Shutter type	orientation	Outside illuminance sun/shade	Daylight factor[2]
1.	RC Primary Catholic School, Kamasondo	5.3	151/922	horizontal	SSE	77,100	0.7%
2.	Romance Junior Secondary School, Kamasondo	8	155/709	Screen	NEE	77,100	1.2%
3.	Primary school West of Kamasondo	5.6	117/742	screen	SSE	70,000	3.7%
4.	RC Rosint School	7.9	172/ 423	horizontal	W	65,400	6.8%
5.	Primary School south of Rokholifa	9.2	140/371	horizontal	W	60,800	n/a
6.	Ahmadiyya Muslim Primary School, Lunsar	5.1	20/42	screen	SSW &EEN	n/a	8.9%
7.	Holy Cross Catholic Primary School, Lunsar	8.1	85/638	horizontal	S	31,800	2%
8.	Marampa Islamic School, Lunsar	6.4	17/195	horizontal	N	66,200	4.5%
9.	District Council School (Government School), Lunsar	3.6	172/512	screen	SSW &EEN	70,000	8.5%
10.	R.C. Primary Adele Pavariani, Lunsar	9.8	43/300	horizontal	SSW &EEN	52,200	13.5%
11.	Sierra Leone Church Primary School, Lunsar	7.0	150/791	screen	N	71,000	8.3%
12.	Moslim Brotherhood Primary and Secondary School, Lunsar	9.2	26/550	screen	N	69,800	1.2%
13.	Catholic Mission Primary School, Lunsar	9.7	324/3320	horizontal	E	n/a	9.8%
	Total Average	7.3	120/732[3]	horizontal		64,700	5.8%

1.6 Comparing the area of openings to the quantitative and qualitative lighting quality

No.	Name	Open area (m^2)	Inside min/max	Qualitative Lighting Characteristics
1.	RC Primary Catholic School, Kamasondo	5.3	151/922	High contrast, high glare, not evenly distributed, dim and poor lighting quality
2.	Romance Junior Secondary School, Kamasondo	8	155/709	Diffuse light due to window type and light-colored walls, good lighting quality
3.	Primary school West of Kamasondo	5.6	117/742	Lighting looks adequate
4.	RC Rosint School	7.9	172/ 423	High contrast and high glare
5.	Primary School south of Rokholifa	9.2	140/371	High contrast and high glare; overall poor lighting quality
6.	Ahmadiyya Muslim Primary School, Lunsar	5.1	20/42	Lighting is adequate except in corner room (L-shaped)
7.	Holy Cross Catholic Primary School, Lunsar	8.1	85/638	High contrast and high glare; overall poor lighting quality
8.	Marampa Islamic School, Lunsar	6.4	17/195	Lighting looks adequate
9.	District Council School (Government School), Lunsar	3.6	172/512	Lighting looks adequate
10.	R.C. Primary Adele Pavariani, Lunsar	9.8	43/300	Lighting looks adequate
11.	Sierra Leone Church Primary School, Lunsar	7.0	150/791	Lighting looks adequate
12.	Moslim Brotherhood Primary and Secondary	9.2	26/550	Poor lighting quality; classrooms

[2] Measured at minimum illuminance. Daylight factor is the interior illuminance divided by the exterior in a shaded area (or overcast sky).

[3] Note that although these are quantitative values, they should only be assessed qualitatively unless compared to the outside illuminance levels for reference (Appendix I).

	School, Lunsar			sometimes held outdoors
13.	Catholic Mission Primary School, Lunsar	9.7	324/3320	Lighting looks adequate
	Total Average	7.3	120/732[4]	Many 100% open windows have glare problems

1.7 Comparing the material and structural elements

No.	Name	Windows	Wall	Truss	Roof	Column
1.	RC Primary Catholic School, Kamasondo	Two wooden shutters per window	Mud brick with stucco	wood	Zinc, new	none
2.	Romance Junior Secondary School, Kamasondo	Decorative concrete blocks	concrete	wood	Zinc, rusted	Square concrete
3.	Primary school West of Kamasondo	Circular screen windows	Concrete, stucco	wood	Zinc, rusted	Square concrete
4.	RC Rosint School	Two wooden shutters per window	Concrete, stucco	wood	Zinc, rusted	none
5.	Primary School south of Rokholifa	Two wooden shutters with rebar per window	Concrete, stucco, 7" thickness	wood	Zinc, rusted	Round concrete
6.	Ahmadiyya Muslim Primary School, Lunsar	Two wooden shutters per window; no rebar	concrete	wood	Zinc, rusted	Square concrete
7.	Holy Cross Catholic Primary School, Lunsar	Two wooden shutters per window	concrete	steel	Zinc, rusted	Two steel widely spaced
8.	Marampa Islamic School, Lunsar	Decorative steel screen	concrete	steel	Zinc, rusted	steel
9.	District Council School (Government School), Lunsar	Decorative concrete blocks	concrete	wood	Zinc, rusted	Square concrete
10.	R.C. Primary Adele Pavariani, Lunsar	Two wooden shutters per window	concrete	steel	Zinc, rusted	none
11.	Sierra Leone Church Primary School, Lunsar	Decorative concrete blocks	concrete	wood	Zinc, rusted	steel
12.	Moslim Brotherhood Primary and Secondary School, Lunsar	Two wooden shutters per window	concrete	wood	Zinc, rusted	steel
13.	Catholic Mission Primary School, Lunsar	Two wooden shutters per window	concrete	steel	Zinc, rusted	none
	Total Average	Two wooden	concrete	wood	Zinc	concrete

[4] Note that although these are quantitative values, they should only be assessed qualitatively unless compared to the outside illuminance levels for reference.

Appendix II

CONTAM output data for the BASE DESIGN

With the model and climate information input to CONTAM, an approximate interior temperature is estimated to reflect temperature increases in the classroom. Once CONTAM outputs a volumetric flow rate, the interior temperature is changed to reflect the differences between the calculated interior temperature (using the thermal comfort equation $q = \rho\cdot C_p\cdot V\cdot\Delta T$). The interior temperature is then changed to reflect these differences in an iterative process until the values match. Therefore, the final change in temperature is used by combining the results of CONTAM and the thermal heat loads calculated above.

2.1 Wind-driven flows for the BASE DESIGN at an exterior temperature of 25.3C

Table 2.1.1 : Wind driven outward airflows for the base design per orifice at 0 K change

Orifice	Airflow (sm^3/s)
LeftFront	1.72325
CenterFront	1.72325
Door	1.95824
Total (buoy only)	5.40482

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 5.4 \text{ m}^3\text{/s}$$

$$\Delta T = 2.79 \text{ K}$$

Table 2.1.2: Wind-driven airflows for the base design with 0 K ΔT input into CONTAM

Wind speed	Volumetric Flow (sm^3/s)	ACH	output ΔT
4.16	5.40	2.18	2.79

2.2 Buoyancy flows for the BASE DESIGN at an exterior temperature of 25.3C

Table 2.2.1 Out-ward driven Buoyancy flows for the base design 6 K increase in interior temperature:

Orifice	Airflow (sm^3/s)
LeftFront	0.27982
CenterFront	0.27982
Door	0(all inward)
LeftRear	0.27982
RightRear	0.27982
Total (buoy only)	1.12

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120\ \text{W} / 1.2\ \text{kg/m}^3 \cdot 1000\ \text{J/kg} \cdot 1.12\ \text{m}^3\text{/s}$$

$$\Delta T = 13.48\ \text{K}$$

Table 2.2.2 Out-ward driven Buoyancy flows for the base design 9 K increase in interior temperature:

Orifice	Airflow (sm^3/s)
LeftFront	0.339683
CenterFront	0.339683
Door	0(all inward)
LeftRear	0.339683
RightRear	0.339683
Total (buoy only)	1.358732

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120\ \text{W} / 1.2\ \text{kg/m}^3 \cdot 1000\ \text{J/kg} \cdot 1.36\ \text{m}^3\text{/s}$$

$$\Delta T = 11.10\ \text{K}$$

Table 2.2.3 Out-ward driven Buoyancy flows for the base design 10.4 K increase in interior temperature:

Orifice	Airflow (sm^3/s)
LeftFront	0.363649
CenterFront	0.363649
Door	0(all inward)
LeftRear	0.363649
RightRear	0.363649
Total (buoy only)	1.454596

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120\ \text{W} / 1.2\ \text{kg/m}^3 \cdot 1000\ \text{J/kg} \cdot 1.46\ \text{m}^3\text{/s}$$

$$\Delta T = 10.34\ \text{K}$$

Table 2.2.4: Iterations for wind-driven airflows for the base design with interior ΔT input into CONTAM

ΔT CONTAM input (K)	Volumetric Flow (sm^3/s)	ACH	output ΔT
6	1.12	0.45	13.48
9	1.36	0.55	11.10
10.4	1.46	0.59	10.34

2.3 Buoyancy and wind flows with the BASE DESIGN

Table 2.3.1 Interior temperature increase of 2 K with 4.14 m/s winds

Orifice	Airflow (sm^3/s)
LeftRear	1.10755 + 1.12057
CenterRear	1.10755 + 1.12057
Total (buoy only)	4.45624

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.46 \text{ m}^3\text{/s}$

$\Delta T = 3.39 \text{ K}$

Table 2.3.2 Interior temperature increase of 3 K with 4.14 m/s winds

Orifice	Airflow (sm³/s)
LeftRear	1.10009 + 1.11963
CenterRear	0.10009 + 1.11963
Total	4.43944

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.44 \text{ m}^3\text{/s}$

$\Delta T = 3.40 \text{ K}$

Table 2.3.3 Interior temperature increase of 3.4 K with 4.14 m/s winds

Orifice	Airflow (sm³/s)
LeftRear	1.109708 + 1.11923
CenterRear	1.109708 + 1.11923
Total	4.4457876

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.45 \text{ m}^3\text{/s}$

$\Delta T = 3.40 \text{ K}$

Table 2.3.4 Buoyancy wind wind-driven flows for the base design: iterations

Input ΔT (K)	Volumetric Flow (sm³/s)	ACH	output ΔT (K)
2.0	4.46	1.79	3.39
3.0	4.44	1.79	3.40
3.4	4.45	1.79	3.40

CONTAM output data for the LONG WINDOW DESIGN

2.4 Wind-driven flows for the LONG WINDOW DESIGN at an exterior temperature of 25.3 °C

Table 2.4.1: Per-orifice wind-driven flows in the long design with 0 K change:

Orifice	Airflow (sm³/s)
LeftRear	2.70241
CenterRear	2.70241
Total (buoy only)	5.40482 (same as base wind-only)

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120\ \text{W} / 1.2\ \text{kg/m}^3 \cdot 1000\ \text{J/kg} \cdot 5.40\ \text{m}^3/\text{s}$$

$$\Delta T = 2.79\ \text{K}$$

Table 2.4.2: Wind-driven airflows for the long window design with 0 K ΔT input into CONTAM

Wind speed	Volumetric Flow (sm^3/s)	ACH	output ΔT
2.0	5.40	2.18	2.79

2.5 Buoyancy flows for the LONG WINDOW DESIGN at an exterior temperature of 25.3 °C

2.5.1. Outward buoyancy flows for long window design at 6 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.337703
CenterFront	0.337703
Door	0
LeftRear	0.337703
RightRear	0.337703
Total (buoy only)	1.350812

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$(\Delta T) = 18{,}120\ \text{W} / 1.2\ \text{kg/m}^3 \cdot 1000\ \text{J/kg} \cdot 1.35\ \text{m}^3/\text{s}$$

$$\Delta T = 11.19\ \text{K}$$

2.5.2. Outward buoyancy flows for long window design at 9 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.410062
CenterFront	0.410062
Door	0
LeftRear	0.410062
RightRear	0.410062
Total (buoy only)	1.640248

A.

B. $\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$

C. $(\Delta T) = 18{,}120\ \text{W} / 1.2\ \text{kg/m}^3 \cdot 1000\ \text{J/kg} \cdot 1.64\ \text{m}^3/\text{s}$

D. $\Delta T = 9.2\text{K}$

2.5.3. Outward buoyancy flows for long window design at 9.1 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.412216
CenterFront	0.412216
Door	0
LeftRear	0.412216
RightRear	0.412216
Total (buoy only)	1.648864

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 1.65 \text{ m}^3\text{/s}$$

$$\Delta T = 9.15 \text{ K}$$

2.5.4 Outward buoyancy flows for long window design iterations

Input ΔT (K)	Volumetric Flow (sm^3/s)	ACH	Output ΔT (K)
6.0	1.35	0.54	11.19
9.0	1.64	0.66	9.2
9.1	1.65	0.67	9.15

2.6 Buoyancy and wind flows with LONG WINDOW DESIGN

2.6.1 Inward buoyancy flows for long window design at 6 K interior temperature increase and 4.15m/s wind speeds:

Orifice	Airflow (sm^3/s)
LeftRear	1.06486 + 1.12754
RightRear	1.06486 + 1.12754
Total (buoy only)	4.3848

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.38 \text{ m}^3\text{/s}$$

$$\Delta T = 3.45 \text{ K}$$

2.6.2. Inward buoyancy flows for long window design at 3.4 K interior temperature increase and 4.15m/s wind speeds:

Orifice	Airflow (sm^3/s)
LeftRear	1.09028+ 1.12573
RightRear	1.09028+ 1.12573
Total (buoy only)	4.43202

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.43 \text{ m}^3\text{/s}$$

$$\Delta T = 3.41 \text{ K}$$

2.6.3. Outward buoyancy flows for long window design iterations

Input ΔT (K)	Volumetric Flow (sm^3/s)	ACH	Output ΔT (K)
6.0	4.38	1.77	3.45
5.0	3.41	1.78	3.41

CONTAM output data for the FIVE WINDOW DESIGN

2.7 Wind-driven flows for the FIVE WINDOW DESIGN at an interior & exterior temperature of 25.3 °C

Table 2.7.1:Wind driven flows(4.16m/s) for the five window design per orifice

Orifice	Airflow (sm^3/s)
LeftRear	1.93834
CenterRear	1.93834
RightRear	1.93834
Total (buoy only)	5.81502

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 5.82 \text{ m}^3\text{/s}$$

$$\Delta T = 2.59 \text{ K}$$

Table 2.7.2: Wind-driven airflows for the five window design with 0 K ΔT input into CONTAM

Wind speed	Volumetric Flow (sm^3/s)	ACH	output ΔT
4.16	5.82	2.35	2.59

2.8 Buoyancy-driven flows for the FIVE WINDOW DESIGN

2.8.1 Outward buoyancy flows for five window design at 6 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.225359
CenterFront	0.225359
Door	0
LeftRear	0.225359
RightRear	0.225359
CenterRear	0.225359
Total (buoy only)	1.126795

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 1.13 \text{ m}^3\text{/s}$$

$$\Delta T = 13.36 \text{ K}$$

2.8.2 Outward buoyancy flows for five window design at 11 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.30068

CenterFront	0.30068
Door	0
LeftRear	0.30068
RightRear	0.30068
CenterRear	0.30068
Total (buoy only)	1.5034

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

ΔT = 18,120 W / 1.2 kg/m^3 · 1000 J/kg · 1.50 m^3/s

ΔT = 10.07 K

2.8.3 Outward buoyancy flows for long window design at 10.3 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.291552
CenterFront	0.291552
Door	0
LeftRear	0.291552
RightRear	0.291552
CenterRear	0.291552
Total (buoy only)	1.45776

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

ΔT = 18,120 W / 1.2 kg/m^3 · 1000 J/kg · 1.46 m^3/s

ΔT = 10.34 K

2.8.4 Outward buoyancy flows for five window design iterations

Input ΔT (K)	Volumetric Flow (sm^3/s)	ACH	Output ΔT (K)
6.0	1.13	0.46	13.36
11.0	1.50	0.60	10.07
10.3	1.46	0.59	10.34

2.9 Buoyancy and wind-driven flows for the 5 WINDOW DESIGN at an exterior temperature of 25.3 °C

2.9.1 Outward buoyancy flows with wind for five window design iterations and 4 K interior temperature increase

Orifice	Airflow (sm^3/s)
LeftRear	0.779841 + 0.803504
CenterRear	0.779841 + 0.803504
RightRear	0.779841 + 0.803504
Total (buoy only)	4.750035

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

ΔT = 18,120 W / 1.2 kg/m^3 · 1000 J/kg · 4.75 m^3/s

$$\Delta T = 3.18 \text{ K}$$

2.9.2 Outward buoyancy flows with wind for five window design iterations and 3.1 K interior temperature increase

Orifice	Airflow (sm^3/s)
LeftRear	0.785703 + 0.804023
CenterRear	0.785703 + 0.804023
RightRear	0.785703 + 0.804023
Total (buoy only)	4.769178

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 4.77 \text{ m}^3\text{/s}$$

$$\Delta T = 3.17 \text{ K}$$

2.9.3Outward buoyancy flow with wind for long window design iterations

Input ΔT (K)	Volumetric Flow (sm^3/s)	ACH	output ΔT (K)
4.0	4.75	1.92	3.18
3.1	4.77	1.92	3.17

Appendix 3: CONTAM, The "Rainy Day" condition

3.1 Wind-driven flows for the RAINY DAY CONDITION (rear windows closed)

Table 3.1.1: Wind driven flows(4.16m/s) for the rainy day design per orifice

Orifice	Airflow (sm^3/s)
LeftFront	0
RightFront	0
Door	0
Total (buoy only)	0

Table 3.1.2: Wind-driven airflows for the rainy day design with 0 K ΔT input into CONTAM

Wind speed	Volumetric Flow (sm^3/s)	ACH	output ΔT
4.16	0	0	N/A

3.2 Buoyancy-only flows for the RAINY DAY CONDITION (rear windows closed)

3.2.1 Outwards buoyancy flows for five window design at 11 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.401767 + 0.109572
CenterFront	0.401767 + 0.109572
Door	0 (inward flows only)
Total (buoy only)	1.022678

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

ΔT = 18,120 W / 1.2 kg/m^3 · 1000 J/kg · 1.02 m^3/s

ΔT = 14.80 K

3.2.2 Outward buoyancy flows for five window design at 13 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.434267 + 0.119465
CenterFront	0.434267 + 0.119465
Door	0
Total (buoy only)	1.107

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

ΔT = 18,120 W / 1.2 kg/m^3 · 1000 J/kg · 1.11 m^3/s

ΔT = 13.60 K

3.2.3 Outward buoyancy flows for long window design at 13.3 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.438872 + 0.120887
CenterFront	0.438872 + 0.120887
Door	0
Total (buoy only)	1.119518

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

ΔT = 18,120 W / 1.2 kg/m^3 · 1000 J/kg · 1.12 m^3/s

ΔT = 13.48 K

3.2.4 Outward buoyancy flows for five window design iterations

Input ΔT (K)	Volumetric Flow (sm^3/s)	ACH	Output ΔT (K)
11.0	1.02	0.41	14.80
13.0	1.11	0.45	13.60
13.3	1.12	0.45	13.48

3.3 Buoyancy flows with wind for the RAINY DAY CONDITION (rear windows closed)

3.3.1 Outward buoyancy flows with wind for long window design at 13.3 K interior temperature increase:

Orifice	Airflow (sm^3/s)
LeftFront	0.438872 + 0.120887
CenterFront	0.438872 + 0.120887
Door	0
Total (buoy only)	1.119518

$$\Delta T = \frac{q_{total}}{\rho \cdot C_p \cdot V}$$

$$\Delta T = 18{,}120 \text{ W} / 1.2 \text{ kg/m}^3 \cdot 1000 \text{ J/kg} \cdot 1.12 \text{ m}^3\text{/s}$$

$$\Delta T = 13.48 \text{ K}$$

3.3.2. Outward buoyancy flows with wind for five window design iterations

Input ΔT (K)	**Volumetric Flow (sm^3/s)**	**ACH**	**Output ΔT (K)**
13.3	1.12	0.45	13.48